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A Computerized Process Control System for the ORR-PSF Irradiation Experiment

Part 2: Mathematical Basis and Computer Implementation of the Temperature Control Algorithm

L. F. Miller

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A COMPUTERIZED PROCESS CONTROL SYSTEM FOR THE ORR-PSF IRRADIATION EXPERIMENT

PART 2: MATHEMATICAL BASIS AND COMPUTER IMPLEMENTATION OF THE TEMPERATURE CONTROL ALGORITHM

L. F. Miller

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DESCRIPTION OF THE CONTROL ALGORITHM FOR THE ORR-PSF IRRADIATION EXPERIMENT

L. F. Miller

ABSTRACT

A brief description of the Oak Ridge Reactor Pool Side Facility (ORR-PSF) and of the associated control system is given. The ORR-PSF capsule temperatures are controlled by a digital computer which regulates the percent power delivered to electrical heaters. The total electrical power which can be input to a particular heater is determined by the setting of an associated variac. This report concentrates on the description of the ORR-PSF irradiation experiment computer control algorithm. The algorithm is an implementation of a discrete-time, state variable, optimal control approach. The Riccati equation is solved for a discretized system model to determine the control law. Experiments performed to obtain system model parameters are described. Results of performance evaluation experiments are also presented. The control algorithm maintains both capsule temperatures within a 288°C ±10°C band as required. The pressure vessel capsule temperatures are effectively maintained within a 288°C ±5°C band.

1. INTRODUCTION

The United States Nuclear Regulatory Commission is conducting an extensive research program into characterizations of irradiation effects on various steels. This work is funded through the LWR Pressure Vessel Surveillance Dosimetry Improvement Program.[1] Motivation for this program stems primarily from the fact that approximately twenty of the first built

Light Water Reactors (LWRs) do not have in-place test specimens made of pressure vessel steels. Thus, several irradiations of appropriate steels are being conducted in research reactors at an accelerated rate relative to power reactors. It is desired that the irradiation relative to this report be performed at essentially the same temperature as the pressure vessel of a typical light water reactor. In particular, the temperature of each irradiation capsule is to be maintained at 288°C ±10°C. This is accomplished by control of electrical heaters on the front and back faces of each set of irradiation specimens. Cooling conditions are fixed.

Schematics of the Oak Ridge Reactor Pool Side Facility (ORR-PSF) irradiation experiment are shown in Figs. 1 and 2. Note that two irradiation capsules are employed. One simulates the surveillance capsule placed behind the thermal shield in some LWRs and the other simulates the pressure vessel. A single set of specimens is placed in the simulated surveillance capsule (SSC) and three sets of specimens (see Fig. 2) are placed in the pressure vessel capsule. These correspond to pressure vessel positions of: 1) zero thickness (0T) or surface, 2) one-fourth thickness (1/4T), and 3) one-half thickness (1/2T). A schematic of a capsule and control system is shown in Fig. 3. This report documents the applicable mathematical and experimental considerations required for development of the control algorithm. A digital computer is employed to control the process; hence, the continuous-time model is transformed to a discrete-time model for determining the control law of the discrete-time sampled data system. Presentation of the mathematical development is followed by a presentation of the model identification experiment. Listings of the applicable computer software are given in the Appendix.

2. THEORY

2.1 General Considerations

It is expected that the reactor power will nearly always be constant at 30 MW. Exceptions occur during inadvertent reactor setbacks and planned shutdowns. Thus, the transient response of the control algorithm must have acceptable performance with respect to overshoot and settling time. The dynamic response with respect to tracking is not very important, however. Steady-state control of the spatial temperature distribution is the item of primary concern.

There is a variety of options with regard to methods for implementing a control algorithm. Several state variable approaches include: 1) eigenvalue placement, 2) output feedback stabilization, and 3) optimal control. Each of these methods could be implemented as a discrete- or as a continuous-time algorithm. Regardless of the choice, a continuous-time model is required.

2.2. Development of the Continuous-Time Model

The partial differential equation, with minor assumptions, which describes the temperature distribution within the experiment capsule is given by

$$\dot{T}(\underline{r},t) = \alpha\nabla^2 T(\underline{r},t) + \frac{\dot{q}'''(\underline{r},t)}{\rho C_p} \qquad (2\text{-}1)$$

where

$\alpha = k/\rho C_p$

$\dot{q}'''$ = internal heat generation

ρ = material density

C_p = heat capacity

k = thermal conductivity

T = temperature.

Equation (2-1) can be discretized to form a set of ordinary differential equations of the form

$$\dot{\underline{T}}(t) = \underline{\underline{A}}\, \underline{T}(t) + \dot{\underline{W}}(t) \qquad (2\text{-}2)$$

where

$\dot{\underline{W}}$ = vector which represents the internal heating associated with each temperature node,

$\underline{T}$ = vector of temperatures corresponding to selected spatial locations,

$\underline{\underline{A}}$ = coefficient matrix which represents the coupling between temperature nodes.

The internal heating rate, $\dot{\underline{W}}(t)$, may be broken into components which represent the gamma heating, $\dot{\underline{W}}_\gamma(t)$, and electrical heating, $\dot{\underline{W}}_e(t)$, so that

$$\dot{\underline{W}}(t) = \dot{\underline{W}}_\gamma(t) + \dot{\underline{W}}_e(t). \qquad (2\text{-}3)$$

Note that the internal heating rate vectors, $\dot{\underline{W}}_\gamma$ and $\dot{\underline{W}}_e$ may be represented in terms of measurable parameters which gives

$$\dot{\underline{W}}_\gamma(t) = \underline{K}\, P_R(t) \qquad (2\text{-}4)$$

$$\dot{\underline{W}}_e(t) = \underline{\underline{B}}\, \underline{P}_e(t) \qquad (2\text{-}5)$$

where

$P_R(t)$ = reactor power,

$\underline{P}_e(t)$ = vector of electrical heater powers,

$\underline{K}$ = vector which converts reactor power to gamma heating,

$\underline{\underline{B}}$ = matrix which converts electrical heater power to internal heating.

If equations 2-3 through 2-5 are substituted into equation 2-2, one obtains,

$$\dot{\underline{T}}(t) = \underline{\underline{A}}\,\underline{T}(t) + \underline{K}\,P_R(t) + \underline{\underline{B}}\,\underline{P}_e(t). \tag{2-6}$$

Equation 2-6 is linear and could be employed directly in a set point tracking control algorithm;[2] however, the regulator problem is easier to implement. Consequently, equation 2-6 is expanded about a reference operating point. This yields,

$$\delta\dot{\underline{T}}(t) = \underline{\underline{A}}\,\delta\underline{T}(t) + \underline{\underline{B}}\,\delta\underline{P}_e(t) + \underline{K}\,\delta P_R(t) \tag{2-7}$$

where

$$\delta\underline{T}(t) = \underline{T}(t) - \underline{T}_o\,,$$
$$\delta P_R(t) = P_R(t) - P_{Ro},$$
$$\delta\underline{P}_e(t) = \underline{P}_e(t) - \underline{P}_{eo}\,.$$

These conversion data, $\underline{K}$ and $\underline{\underline{B}}$, are identified by considering steady-state perturbation about the reference operating point. A first order Taylor series expansion gives,

$$\delta\underline{T}_{ss} = \left[\frac{\partial\ \delta\underline{T}}{\partial\ \delta P_R}\right]\delta P_R + \left[\frac{\partial\ \delta\underline{T}}{\partial\ \delta\underline{P}_e}\right]\delta\underline{P}_e\ . \tag{2-8}$$

Note that at steady state, $\delta\dot{\underline{T}}(t) = 0$. Thus, if equation 2-8 is substituted into 2-7, restricted to steady-state, one identifies directly that

$$\underline{\underline{B}} = -\underline{\underline{A}}\left[\frac{\partial\ \delta\underline{T}}{\partial\ \underline{P}_e}\right] \tag{2-9}$$

and

$$K = -\underline{\underline{A}} \left[\frac{\partial\ \underline{\delta T}}{\partial\ P_R} \right] \quad . \tag{2-10}$$

The partial derivatives of interest are obtained by perturbations of electrical heaters and reactor power. The system matrix, $\underline{\underline{A}}$, is obtained by analysis of time response data.

If variations in reactor power are neglected, one obtains the following for the continuous-time model:

$$\dot{\underline{X}}(t) = \underline{\underline{A}}\ \underline{X}(t) + \underline{\underline{B}}\ \underline{U}(t) \tag{2-11}$$

where

$\underline{X}(t) = \underline{\delta T}(t)$,
$\underline{U}(t) = \underline{\delta P}_e(t)$.

Equation 2-11 employs the usual nomenclature for representing dynamical systems in modern control theory text books. If reactor power variations are included, the continuous time model becomes,

$$\dot{\underline{X}}(t) = \underline{\underline{A}}\ \underline{X}(t) + \underline{\underline{B}}\ \underline{U}(t) + \underline{K}\ V(t) \tag{2-12}$$

where

$V(t) = \delta P_R(t)$.

In order to employ a discrete-time algorithm, equation 2-11 must be transformed to a discrete-time system.[3]

2.3 Transformation from a Continuous- to a Discrete-Time Model

The solution to equation 2-11 is given by

$$\underline{X}(t) = e^{\underline{\underline{A}}t} \; \underline{X}(0) + \int_{0}^{t} e^{\underline{\underline{A}}(t-\tau)} \; \underline{\underline{B}} \; \underline{U}(\tau) \, d\tau \quad . \tag{2-13}$$

If we consider a discretized system sampled at intervals of time T, one obtains,[3]

$$\underline{X}(n + 1) = e^{\underline{\underline{A}}T} \; \underline{X}(n) + \left(\int_{0}^{T} e^{A\alpha} d\alpha \right) \underline{\underline{B}} \; \underline{U}(n), \tag{2-14}$$

which may be written as

$$\underline{X}(n + 1) = \tilde{\underline{\underline{A}}} \; \underline{X}(n) + \tilde{\underline{\underline{B}}} \; \underline{U}(n) \tag{2-15}$$

where $\tilde{\underline{\underline{A}}}$ and $\tilde{\underline{\underline{B}}}$ are defined implicitly.

Note that when $\underline{\underline{A}}$ is time independent and $\underline{U}$ is constant over each time interval,

$$\tilde{\underline{\underline{A}}} = \underline{\underline{e}}^{\underline{\underline{A}}T} \tag{2-16}$$

and

$$\tilde{\underline{\underline{B}}} = \left(\underline{\underline{e}}^{\underline{\underline{A}}T} - \underline{\underline{I}} \right) \; \underline{\underline{A}}^{-1} \; \underline{\underline{B}} \tag{2-17}$$

$$\underline{\underline{B}} = \underline{\underline{H}} \; \underline{\underline{B}} \quad . \tag{2-18}$$

The matrices $\tilde{\underline{\underline{A}}}$ and $\underline{\underline{H}}$ are easily computed by expanding the matrix exponential in an infinite series until convergence is obtained. The subroutine which performs this calculation, DSCTIZ, is listed in the Appendix as part of program RCTEQ.

2.4 Determination of Closed-Loop-State-Variable Control Laws

2.4.1 Discussion of Choice of Methods

Implementation of a discrete-time control algorithm with a continuous-time system could be accomplished in a variety of ways. First, one has the choice of calculating the control law with either eigenvalue placement or optimal methods. The choice is more personal than technical. In neither case can performance parameters such as settling time and overshoot be specified a priori. Input parameters must be adjusted for both methods to obtain acceptable transient response characteristics. Steady-state conditions should be the same regardless of the method for determining the control law. An optimal method is used for this work.

Given the choice that an optimal method is to be used, a control law could be determined for the continuous-time system and then the closed-loop system discretized; alternatively, the open-loop system could be discretized and a control law determined for a discrete-time system. The second option is utilized.

2.4.2 Determination of an Optimal Control Law for a Discrete-Time System

The optimal control law is obtained by solving the discrete-time Riccati equation. The procedure employed is one given by Kirk[4] and is paraphrased herein. The system under consideration is described by equation 2-15.

A fairly general problem is to find an optimal control policy $U^*[X(k),k]$ that minimizes the performance measure

$$J = 1/2\ X^T(N)H\ X(N) + 1/2 \sum_{k=o}^{N-1} [X^T(k)Q(k)X(k) + U^T(k)R(k)U(k)] \qquad (2\text{-}19)$$

where

H and Q are real symmetric positive semi-definite $n \times n$ matrices,
R is a real symmetric positive definite $M \times M$ matrix,
n is the number of system states,
M is the number of control variables, and
N is a positive integer greater than 0.

The problem considered herein is simpler than the one stated by equation 2-19. In particular, the system in question, an irradiation capsule, is assumed to be time-invariant and completely controllable. In addition, it is assumed that the system states and controls are not constrained.

In order to evaluate the feedback gains, it is necessary to solve the equations

$$F(N - K) = -[R + \tilde{B}^T\ P(K-1)\tilde{B}]^{-1}\ \tilde{B}^T\ P(K-1)\tilde{A} \qquad (2\text{-}20)$$

and

$$P(K) = [\tilde{A} + \tilde{B}\ F(N-K)]^T\ P(K-1)[\tilde{A} + \tilde{B}\ F(N-K)]$$
$$+ F^T(N-K)R\ F(N-K) + Q, \qquad (2\text{-}21)$$

with $P(0) = H$. Note that if the system is completely controllable and time invariant, $H = 0$, and R and Q are constant matrices. In this case the optimal control law is time-invariant for an infinite-stage process.

In particular, $F(N - K)$ converges to a constant matrix as N becomes sufficiently large. Thus, the feedback law can be implemented with constant gain factors.

The numerical evaluation of the feedback matrix F is relatively straightforward. Care must be employed, however, in determining convergence since the convergence rate may be nonuniform. The computer program for this calculation, RCTEQ,[5] solves either the continuous- or discrete-time Riccati equation.

2.5 Computational Methods

Two computer programs are employed to determine and evaluate the control algorithm. One program, RCTEQ, is used for solving the discrete-time Riccati equation and the other, MVTR2, is used for determining the transient response.

RCTEQ is written to solve either the continuous- or discrete-time Riccati equation. Discretization of the continuous-time model is accomplished by subroutine DSCTIZ. A listing of RCTEQ is given in the Appendix. MVTR2 is not listed since results from simulation runs are not included in this report. The reason for not including MVTR2 and the simulation runs is that the simulation results are of essentially no value. A discussion regarding the simulation runs is given in section 3.2. Results from RCTEQ for the surveillance capsule are given in Table 1, and for the pressure vessel capsule they are given in Tables 2 through 4.

3. EXPERIMENTS AND RESULTS

3.1 Experimental Determination of the System and System Input Matrices

The experimental procedure for determining the system matrix (A) and the system input matrix (B), defined by equation 2-11, relies on the control system hardware. Consequently, a brief description of the system configuration is presented.

Fig. 3 is a simplified representation of the process control system hardware. Note that the schematic shown in Fig. 3 is essentially the same for the surveillance position and the three pressure vessel positions; consequently, only the single schematic is presented. Refer to ORNL/NUREG/TM-405/P1 by S. H. Merriman for additional details. Five heaters are on the front side facing the reactor and five are on the back side of each specimen assembly. Of the thermocouples input to the computer, ten are on the front face and ten are on the back face of each set of irradiation specimens. Several others are input to recorders for protecting the experiment in case of computer failure.

The system input matrix (B) is determined in part from a partial derivative matrix. In particular, the (B) matrix is determined from changes in temperature of all thermocouples due to a power change of a single heater and from the system matrix (A). The procedure employed is as follows:

1. Verify that all variacs are set to zero and that no solid state relay (SSR) is fired.
2. Record baseline data and ensure that steady-state conditions prevail.
3. Set the selected variac (i) to a position that will yield a temperature increase of approximately 15°C.
4. Fire the SSR associated with variac (i) at 100%. Record variac setting, voltage, and current for the associated heater.

5. Record temperature data at 40 second intervals until steady-state conditions prevail. This requires approximately one hour.
6. Set all variacs to zero and terminate firing all SSRs.
7. Wait for temperatures to return to steady state. This also requires about one hour.
8. Repeat steps 2 through 7 for all variacs.

The data from this experiment are sufficient for determining the $\underline{\underline{A}}$ and $\underline{\underline{B}}$ matrices defined by equation 2-6. Note that the units of the partial derivative matrix, determined by changes in temperatures with respect to a change to electrical heater power, are C° per watt and that the control hardware adjusts the fractional power input to each heater. Consequently, the variac setting and corresponding heater power must be employed by the control algorithm. Steady-state data from this experiment are given in Tables 5 through 8. Table 5 contains data for the surveillance capsule. The variac setting, voltage, current, heater power, and conversion factors for obtaining heater power from the variac setting are given for each case; in addition, the partial derivative matrix data are listed. Approximately twenty hours are required to collect the heat-up and cool-down data for all ten variacs. The same data for the pressure vessel capsule are listed in Tables 6 through 8. Note that a set of data is obtained for each irradiation specimen set. Each set of irradiation specimens is separated from adjacent specimens by cooling water channels; hence, it is assumed that each of the three capsule regions is decoupled.

Transient data are illustrated in Figs. 4 and 5. Surveillance capsule data are given in Fig. 4. Both heat-up and cool-down data are shown. A second order response is clearly indicated by the heat-up response but is not indicated by the cool-down response. In each case, however, an effective first order time constant of approximately 12 minutes is indicated. This is the case for the response of several individual thermocouples as well as the average of several thermocouples. The system matrix is represented as a diagonal matrix with each entry defined by the reciprocal of the effective first order time constant. A more accurate identification of the system matrix "A" would result in a control system with better dynamic characteristics but would probably not significantly impact the steady-state spatial control. The response of a selected thermocouple resulting from heating the pressure vessel capsule is given in Fig. 5. This response indicates that the dynamical model is essentially first order with an effective time constant of 20 minutes.

The sampling interval for a discrete-time control system should be shorter than one-fifth of the shortest effective time constant. Thus, a two-minute sampling interval would be acceptable. The sampling interval utilized, 40 seconds, is considerably shorter than the maximum acceptable.

3.2 Performance Evaluations

3.2.1 Computer Simulations

Evaluations of the control algorithm are either computer simulations with the system model or real-time test runs. Computer simulation calculations are based on an optimal control law obtained from a solution of a Riccati equation with 500 on the diagonal of the system mode weighting matrix (the "Q" matrix of equation 2-19). Results from the computer simulation indicate satisfactory performance. However, several real-time test runs indicate oscillatory control. This is an indication that the feedback gains are too large. Disagreement between the simulation runs and the real-time test runs is probably due to a relatively crude model of the system matrix. Significant effort would be required to obtain an accurate identification of this matrix. In order to eliminate the problem with oscillations, the feedback law is recalculated with a system mode weighting matrix with ten on the diagonal.

3.2.2 Low Temperature Real-Time Tests and Control Algorithm Parameter Selections

Low temperature real-time tests are performed with several control algorithms. First, the effect of changing the system mode weighting matrix (SMWM) of the Riccati equation is evaluated from several test runs on the surveillance capsule. A SMWM with ten on the diagonal resulted in a feedback law with acceptable performance, but, with 500, it resulted in oscillatory performance. This evaluation is obtained with an algorithm that controlled only the average temperature and with an algorithm that regulated each variac individually to control the temperature distribution.

Because the reference setpoint for heater power cannot be easily established with manual operation of the variacs and because this setpoint changes during the fuel cycle, an integrating component is needed in the algorithm. The relative values of proportional and integral gains is established from several real-time test runs on the surveillance capsule. Difficulties with all integral control compared with a combination of proportional plus integral control are: 1) the response to perturbations is slower, and 2) overshoot is more pronounced. Complete proportional control is unacceptable since the setpoint changes during the fuel cycle and the required heater power for a flat capsule temperature cannot be easily determined.

The algorithm implemented integrates the reference heater power setpoint only during steady-state conditions. Thirty percent of the demanded duty cycle change is added to the reference duty cycle every 80 seconds when steady-state conditions prevail. The criteria for steady state is that the average capsule temperature changes less than 1°C in 80 seconds.

Another feature of the algorithm is that a transfer between automatic and on/off control is made within a hysteresis band. Transfer to automatic control is made when the average temperature is within 2°C and transfer out is made when the average temperature exceeds 5°C.

Most of the control algorithm parameters can be changed from the terminal at initialization time. Some are fixed by the program. The values mentioned above are default parameters. Examples of three tests are given in Fig. 6. A brief description of each test follows:

A. Proportional only,

B. Integral only, and

C. Average temperature.

Note that restarts are shown for cases A and B.

3.3 Experimental Determination of Temperature Changes Due to Changes in Reactor Power

The ORR is occasionally operated at power levels between 24 and 30 MW for short periods of time. During these intervals, electrical heater power must be substituted for the loss of radiation heating. If reactor power is used as an input signal, the electrical heater power demand can be increased immediately after the reactor power decrease is detected rather than waiting for detectable changes in capsule temperature.

Data required for implementing this control option are partial derivatives of capsule temperature changes due to reactor power changes. These data are obtained with the following experimental procedure:

1. Establish the ORR power at 24 MW with the ORR-PSF irradiation capsule in place with no electrical heating.
2. Maintain reactor power at 24 MW until temperatures are stabilized. This requires about one hour.
3. Record stabilized data at 24 MW.
4. Repeat steps 1 through 3 for a power level of 30 MW.

Data varied very little within a particular set of irradiation specimens; consequently, averaged data are presented. These results are listed in Table 9.

4. PROCESS CONTROL SOFTWARE

4.1 General Description

Details regarding the process control system, except for the control algorithm, are given by Merriman.[6] A schematic is shown in Fig. 7. Note that the one-shots must be fired every 200 ms and that the control demand is modified every 40 seconds. Thus, there are 200 time frames in which various functions must be performed. Thirty-six out of the 200 frames are utilized for computing the control demand. During these 36 time frames, however, the software for firing the one-shots is also executed. Other functions such as: 1) reading analog data, 2) data conversions, and 3) data output are executed during selected time frames.

4.2 Description of the Control Subroutine

The subroutine which computes the percent of time the heaters should be on (i.e., the duty cycle) may function in a variety of modes. Not only can several different methods be selected, but also, parameters which define a particular method can be adjusted. The description of the control subroutines, CNTRL, is accomplished in several parts: 1) control methods, 2) fixed program control parameters, and 3) program structure.

4.2.1 Control Methods

Three fundamentally different control options are available: 1) an optimal/integral regulator approach which employs a feedback law based on the solution of the discrete-time Riccati equation, 2) a proportional plus integral control of the average temperature, and 3) the percent of time the heaters are on is fixed. Each method is discussed separately.

The optimal/integral regulator adjusts each heater duty cycle separately. The demand change for a particular control interval, 40 seconds, is based on the feedback matrix "F", and the deviation of applicable thermocouples from the specified reference temperature. The actual duty cycle is based on the reference duty cycle, which is integrated, plus the demanded change. In order to prevent accumulation in the integration of a very small demand, the reference duty cycle is not adjusted (integrated) unless the demanded change is greater than a specified value at a particular point in time. Also, the integration is not performed if steady-state conditions are not established. Program control parameters are also utilized for establishing the relative integral versus proportional control. Steady state is determined from a selected change in average temperature over a selected period of time. Two parameters are employed to set a switch to establish steady-state conditions. Parameter values are based on several low temperature tests of the algorithm.

For the case of average temperature control, a classical proportional plus integral approach is used. The reset (integration) criteria are the same as for the optimal/integral method. The proportional gain is based on low temperature evaluations of the algorithm.

A fixed duty cycle may be specifed by the selection of a particular input parameter. Also, the demand change in electrical heater power may be printed. For details, the reader is referred to the listing in the Appendix.

4.2.2 Program Control Parameters

Program control parameters fall into three categories: 1) those which may be input from the terminal, 2) those set in a specified value in CNTRL, and 3) those passed through COMMON statements. The parameters which may be specified from the terminal and the associated description are listed below.

Variable Name (Default Value)	Description
IPCTR	Set to 1 if default data are to be changed.
TREF (288.0)	Reference temperature at which the capsules are to be controlled.
ICMTH (1)	Automatic Control Method: 1. Optimal/Integral Regulator. The discrete-time Riccati equation is solved to determine the feedback coefficients. 2. Control only the average temperature. 3. Duty cycle is fixed at 80 and the optimal/integral control law is output. >3. Duty cycle fixed at ICMTH.
ATCL (2.0)	Band for transferring from on/off (50/100 duty cycle) control to method 1 or 2 as specified by ICMTH. Hysteresis of three degrees is included in the switch (IUDTR).
TAVDM (1.0)	Maximum deviation in the average temperature in NTAU 40 second intervals for determining steady-state conditions.
IDSTR (0)	Set to 1 to offset control demand by the deviation of reactor power from 30 MW.
TDB (3.0)	Temperature dead band for control action.
DPCOFC (1.0)	Multiplies the demand change of duty cycle (overall proportional gain).
DPCOFI (0.3)	Multiplies the demand change which is added to the present reference duty cycle (overall integral gain).

The parameters fixed in subroutine CNTRL are as follows:

Variable Name	Description
CFAC (10,4)	Conversion factors to convert variac setting to heater power.
DTDPX (20,4)	Partial derivatives of temperature with respect to reactor power for each thermocouple associated with each specimen set.
NTMP	Number of thermocouples associated with each specimen set.
NHTR	Number of heaters associated with each specimen set.
NTAU	Number of sampling interval over which the rate of change of the average temperature is determined.
XLMT	Minimum control demand for integrating the reference setpoint.

Information regarding variables passed through COMMON is given by Merriman.[6] It is also worthwhile to note that all of the input parameters need not be input if default values are accepted. Refer to the listing in the Appendix and to the input description for default values.

4.2.3 Program Structure

The time required to calculate the control demand for each 40 second sampling/control interval is longer than 200 ms, (i.e., 12 CPU clock cycles). One-shots, which fire the solid state relays, must receive new instructions every 200 ms. Thus, this overhead must be accounted for in each 0.2 second interval. The remainder of each 0.2 second interval is available for performing other calculations. Consequently, several calls to CNTRL are required during each 40 second interval.

There are four basic functional sections in subroutine CNTRL:

1. Program initialization and data input,
2. Tests for erratic or bad temperature data,
3. Calculation of demanded heater power changes by multiplying a 10×20 matrix times a temperature vector, and
4. Calculation of the heater duty cycle for the next 40 second interval by one of the requested methods.

These four calculations must be accomplished for each set of irradiation specimens. Block diagrams of subroutine CNTRL are given by Figs. 8 and 9.

5. CONCLUSIONS AND RECOMMENDATIONS

A state variable, computer controlled, control algorithm is implemented for maintaining temperature control of the ORR-PSF irradiation capsules. The automatic algorithm maintains temperatures within a band about 25% smaller than can be readily accomplished with manual control. In principle, one should be able to accomplish the same precision of steady-state control by manual adjustment of the variacs as with computer control. Automatic control allows for more timely and precise adjustments to perturbations. It also allows adjustments for power distribution changes during the fuel cycle. The algorithm implemented accomplishes this objective very well. Improved performance could probably be obtained if the system matrix contained coupling terms rather than only first order dynamics. Other items of concern are that: 1) the system is not completely controllable,[4] and 2) control variables are bounded. The first item does not show up from the mathematical model, but is apparent from experiment results. In particular, all of the temperatures included in the model (i.e., 20 per specimen set) cannot be driven to a specified temperature simultaneously by manual adjustment of the variacs. This is a clear indication that the system as configured is not controllable. If fewer temperatures were included in the system model (i.e., less than the number of heaters) and if no controls were bounded, then the model temperatures could be driven to the specified temperatures. Another modification that would improve performance is to treat all three specimen sets in the pressure vessel capsule as coupled. Even though water channels exist between them, it is apparent when a particular heater is energized that they are not decoupled. The control algorithm is based on the assumption that each region of the pressure vessel capsule is decoupled.

Improved performance could be obtained if the following changes were made:

1. Relax the number of thermocouple temperatures to be controlled. Approximately half of the present demand, i.e., 20, could probably be maintained at the desired temperature of 288°C.
2. Obtain a better model of the system matrix "A" and of the system input matrix "B". This could be accomplished by a parameter identification experiment for the system matrix. The experiment used for determining "B" for each capsule set should be repeated with each heater treated separately.
3. Treat the pressure vessel capsule as a single entity rather than three decoupled regions.

These changes involve substantial effort and their implementation would yield some improvement in temperature control; thus, it is recommended that these improvements be incorporated. It would be a worthwhile endeavor from the standpoint of methodology development and from the expected improvement in performance even though the improved performance would not be substantial.

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Table 1. Feedback Matrix for the Surveillance Capsule

Row	Column Numbers				
	1	2	3	4	5
	6	7	8	9	10
	11	12	13	14	15
	16	17	18	19	20
1	.014	-.0164	.00172	-.0073	.0098
	-.093	-.00132	-.0384	-.0382	-.0357
	-.0446	-.041	-.0395	-.2916	-.2078
	-.3217	-.234	-.291	-.197	-.259
2	-.012	-.017	-.0488	-.0683	-.111
	-.22	-.241	-.00933	-.0002	-.116
	-.11	-.388	-.429	.0083	-.018
	-.037	-.077	-.107	-.221	-.217
3	-.0578	-.0994	-.127	-.213	-.136
	-.14	-.0608	-.0871	-.0787	-.223
	-.251	-.052	-.0782	-.0502	-.124
	-.121	-.204	-.137	-.122	-.0468
4	-.248	-.263	-.141	-.103	-.05
	-.0263	-.0193	-.3906	-.447	-.0603
	-.085	-.0216	-.0252	-.20	-.252
	-.136	-.1	-.0576	-.0444	-.24
5	-.341	-.25	-.365	-.247	-.3396
	-.2018	-.3195	-.0394	-.0466	-.0707
	-.0697	-.057	-.06345	-.0123	-.0419
	-.0428	-.0455	-.0349	-.0308	-.0179
6	-.0198	-.0149	-.00964	-.0168	-.024
	-.0174	-.0196	-.0732	-.0731	-.0783
	-.0713	-.0737	-.066	-.224	-.164
	-.212	-.166	-.227	-.167	-.213
7	-.208	-.0011	-.0356	-.0737	-.11
	-.212	-.208	-.0484	-.0515	-.129
	-.113	-.403	-.3605	-.127	-.0239
	-.0557	-.0754	-.0926	-.171	-.159

Table 1. Feedback Matrix (Cont'd)

Row	Column Numbers 1 / 6 / 11 / 16	2 / 7 / 12 / 17	3 / 8 / 13 / 18	4 / 9 / 14 / 19	5 / 10 / 15 / 20
8	-.0585	-.0983	-.0994	-.202	-.122
	-.126	-.0508	-.09	-.0962	-.217
	-.197	-.0560	-.0598	-.298	-.0824
	-.0510	-.105	-.0537	-.0533	-.0214
9	-.247	-.2512	-.107	-.0735	.0303
	-.0788	.0001	-.459	-.384	-.0704
	-.063	.0024	-.008	-.166	-.178
	-.083	-.0474	-.0164	-.00957	.011
10	-.0679	-.244	-.324	-.234	-.206
	-.227	-.316	-.059	-.0534	-.0457
	-.0514	-.0477	-.0607	.0155	.00214
	.0127	.0004	.0051	-.00023	.0028

Table 2. Feedback Matrix for the OT Position of the Pressure Vessel Capsule

Row	Column Numbers 1 6 11 16	 2 7 12 17	 3 8 13 18	 4 9 14 19	 5 10 15 20
1	.0540	.0413	.0509	.0410	.0536
	.0966	.0907	-.0120	-.0371	-.0436
	-.0597	-.311	-.0434	-.445	-.356
	-.446	-.322	-.396	-.313	-.353
2	.0081	-.0098	-.0379	-.100	-.171
	-.340	-.397	-.0419	-.0367	-.182
	-.195	-.651	-.713	.0293	-.0338
	-.0326	-.0959	-.172	-.307	-.340
3	-.087	-.178	-.210	-.240	-.197
	-.197	-.071	-.076	-.111	-.390
	-.441	-.132	-.117	-.079	-.176
	-.179	-.257	-.162	-.135	.00257
4	-.441	-.442	-.221	-.124	-.0145
	.0106	.0508	-.6124	-.688	-.122
	-.143	-.0353	-.0106	-.370	-.388
	-.206	-.0815	-.0213	.0297	.0850
5	-.499	-.412	-.525	-.403	-.507
	-.356	-.456	-.0140	-.0311	-.0721
	-.0903	-.103	-.0534	-.00520	-.0410
	.0156	-.0063	.0542	.0174	.0446
6	.0039	.0165	.0173	-.0193	-.0302
	-.0428	-.0279	-.142	-.123	-.119
	-.102	-.0472	-.083	-.338	-.304
	-.367	-.367	-.419	-.347	-.447
7	.0097	-.0075	-.0319	-.100	-.178
	-.271	-.313	-.0652	-.0413	-.156
	-.148	-.406	-.406	-.0133	-.00930
	-.0678	-.119	-.203	-.300	-.360

Table 2. Feedback Matrix (Cont'd)

Row	Column Numbers 1 / 6 / 11 / 16	2 / 7 / 12 / 17	3 / 8 / 13 / 18	4 / 9 / 14 / 19	5 / 10 / 15 / 20
8	-.0787	-.137	-.169	-.255	-.213
	-.210	-.141	-.179	-.157	-.306
	-.259	-.0960	-.146	-.109	-.129
	-.184	-.248	-.208	-.186	-.168
9	-.299	-.269	-.181	-.129	-.107
	-.0561	-.0491	-.491	-.402	-.124
	-.0955	.00945	-.0139	-.259	-.231
	-.187	-.168	-.104	-.0767	-.0913
10	-.321	-.263	-.343	-.294	-.360
	-.306	-.357	-.122	-.100	-.0917
	-.0774	-.0525	-.0892	-.0269	.00478
	-.0200	-.0340	-.0619	-.0573	-.0732

Table 3. Feedback Matrix for the 1/4 T Position of the Pressure Vessel Capsule

Row	Column Numbers 1 6 11 16	2 7 12 17	3 8 13 18	4 9 14 19	5 10 15 20
1	.000590	-.0313	-.0356	-.0650	-.0361
	-.0360	-.0184	-.0827	-.0947	-.0951
	-.0982	-.0969	-.101	-.227	-.205
	-.259	-.215	-.255	-.209	-.245
2	-.0406	-.0674	-.0859	-.121	-.153
	-.188	-.214	-.0619	-.0534	-.125
	-.128	-.257	-.278	-.0537	-.0648
	-.0832	-.115	-.136	-.181	-.195
3	-.0834	-.101	-.114	-.152	-.128
	-.111	-.0854	-.0803	-.0903	-.140
	-.150	-.0884	-.0938	-.0743	-.0942
	-.105	-.127	-.111	-.106	-.0800
4	-.249	-.253	-.197	-.186	-.131
	-.101	-.0868	-.327	-.342	-.135
	-.129	-.0767	-.0789	-.231	-.236
	-.179	-.148	-.113	-.0957	-.0790
5	-.205	-.188	-.236	-.218	-.232
	-.185	-.216	-.0912	-.0912	-.0934
	-.0889	-.0943	-.0938	-.0584	-.0656
	-.0631	-.0628	-.0614	-.0694	-.0613
6	-.0789	-.0699	-.0537	-.0481	-.0544
	-.0717	-.0669	-.115	-.110	-.114
	-.119	-.118	-.121	-.205	-.182
	-.212	-.185	-.215	-.201	-.217
7	-.0759	-.0752	-.0825	-.0915	-.124
	-.175	-.185	-.0696	-.0649	-.129
	-.129	-.252	-.243	-.0690	-.0705
	-.0843	-.105	-.127	-.173	-.185

Table 3. Feedback Matrix (Cont'd)

Row	Column Numbers 1 / 6 / 11 / 16	2 / 7 / 12 / 17	3 / 8 / 13 / 18	4 / 9 / 14 / 19	5 / 10 / 15 / 20
8	-.126	-.137	-.139	-.157	-.140
	-.150	-.126	-.132	-.130	-.196
	-.192	-.140	-.139	-.113	-.127
	-.128	-.166	-.143	-.143	-.122
9	-.198	-.191	-.143	-.105	-.0927
	-.0859	-.0863	-.262	-.251	-.121
	-.118	-.0849	-.0813	-.175	-.172
	-.132	-.114	-.0950	-.0860	-.0790
10	-.233	-.200	-.217	-.175	-.211
	-.195	-.212	-.115	-.109	-.113
	-.113	-.117	-.117	-.0756	-.0729
	-.0678	-.0787	-.0757	-.0806	-.0789

Table 4. Feedback Matrix for the 1/2 T Position of the Pressure Vessel Capsule

Row	Column Numbers 1 6 11 16	2 7 12 17	3 8 13 18	4 9 14 19	5 10 15 20
1	.00601	-.0342	.0256	.000370	.0290
	.0207	-.0342	-.0859	-.0331	-.0621
	-.0817	-.0912	-.0766	-.315	-.211
	-.311	-.209	-.373	-.244	-.341
2	-.0289	-.0735	-.0657	-.116	-.157
	-.235	-.0735	-.0257	-.00331	-.169
	-.167	-.376	-.444	-.0329	-.0300
	-.0559	-.0923	-.155	-.240	-.208
3	-.100	-.0789	-.142	-.201	-.158
	-.134	-.0789	-.0924	-.0739	-.185
	-.235	-.0990	-.108	-.0437	-.0638
	-.109	-.167	-.131	-.0950	-.0380
4	-.290	-.300	-.173	-.128	-.0673
	-.0390	-.300	-.275	-.323	-.0914
	-.0834	-.056	-.0018	-.225	-.196
	-.119	-.107	-.0585	-.0440	.0200
5	-.345	-.270	-.329	-.257	-.364
	-.255	-.270	-.0656	-.0577	-.112
	-.110	-.122	-.126	-.0391	-.0289
	-.0405	-.0443	-.031	-.0469	-.00182
6	-.0325	-.0335	-.0378	-.0586	.00018
	-.0573	-.0335	-.0139	-.153	-.149
	-.144	-.119	-.165	-.369	-.344
	-.413	-.343	-.391	-.319	-.398
7	-.0412	-.0458	-.0949	-.127	-.193
	-.306	-.0458	-.0597	-.0951	-.187
	-.176	-.515	-.500	-.0573	-.0946
	-.100	-.139	-.183	-.293	-.288

Table 4. Feedback Matrix (Cont'd)

Row	Column Numbers 1 / 6 / 11 / 16	2 / 7 / 12 / 17	3 / 8 / 13 / 18	4 / 9 / 14 / 19	5 / 10 / 15 / 20
8	-.135	-.179	-.221	-.293	-.207
	-.236	-.179	-.163	-.194	-.334
	-.334	-.17	-.172	-.133	-.193
	-.196	-.283	-.197	-.212	-.182
9	-.335	-.318	-.224	-.150	-.100
	-.0637	-.318	-.528	-.490	-.127
	-.130	-.055	-.0241	-.306	-.306
	-.189	-.138	-.0949	-.0661	-.0739
10	-.359	-.281	-.354	-.293	-.359
	-.288	-.281	-.0996	-.128	-.132
	-.124	-.0929	-.117	-.0512	-.0665
	-.0532	-.0487	-.0355	-.0744	-.0563

Table 5. Partial Derivative Matrix of Surveillance Capsule Temperature Changes Due to Changes in Electrical Heater Power. The units are °C per watt. Data for determining electrical power and the conversion factor (γ) for computing heater power from variac setting are listed below the partial derivative matrix.

Thermo-couple	Variac Number									
	1	2	3	4	5	6	7	8	9	10
1	.0046	.0112	.0229	.0683	.0857	.0114	.0137	.0224	.0657	.0253
2	.012	.0137	.0331	.0731	.0688	.0114	.0110	.0321	.0677	.0633
3	.0072	.0218	.0391	.0451	.0941	.0094	.0192	.0321	.0352	.0813
4	.0098	.0261	.0566	.0362	.0677	.0114	.0274	.0533	.0272	.0613
5	.0046	.0348	.0391	.0219	.0857	.0114	.0343	.0350	.0026	.0546
6	.029	.0609	.0421	.0198	.0583	.0127	.0590	.0378	.0272	.0599
7	.0078	.0652	.0247	.0164	.0836	.0114	.0576	.0212	.0093	.0793
8	.019	.0112	.0307	.1031	.0225	.0255	.0206	.0309	.114	.0226
9	.019	.0093	.0289	.1147	.0239	.0255	.0212	.0321	.0982	.0213
10	.016	.0348	.0566	.0246	.0260	.0241	.0377	.0544	.0239	.0180
11	.018	.0335	.0626	.0301	.0260	.0228	.0343	.0504	.0226	.0193
12	.018	.0969	.0217	.0150	.0239	.0241	.0993	.0212	.0066	.0193
13	.018	.106	.0277	.0164	.0260	.0228	.0911	.0224	.0093	.0226
14	.074	.0093	.0229	.0594	.0140	.0583	.0385	.0712	.0484	.0047
15	.054	.0124	.0361	.0683	.0190	.0436	.0144	.0269	.0497	.0067
16	.078	.0168	.0349	.0417	.0176	.0537	.0212	.0195	.0272	.0033
17	.059	.0261	.0524	.0335	.0190	.0436	.0260	.0310	.0192	.0067
18	.071	.0323	.0379	.0232	.0155	.0564	.0295	.0195	.0113	.0047
19	.051	.0578	.0349	.0198	.0155	.0436	.0473	.0195	.0093	.0067
20	.066	.0578	.0205	.064	.0140	.0550	.0459	.0143	.0080	.0067

Table 5. Partial Derivative Matrix of Surveillance Capsule Temperature (Cont'd)

Variac	Setting(s)	V	I	Power (P)*	γ*
1	15	21.5	7.14	153.51	0.682
2	17	23	7	161	0.557
3	17	24	6.92	166.1	0.574
4	15	20	7.32	146.4	0.651
5	8.5	20	7.12	142.4	1.971
6	16.5	21	7.10	149.1	0.548
7	16	21	6.95	145.95	0.570
8	18.5	24.6	7.12	174.44	0.510
9	15.5	20.5	7.35	150.68	0.627
10	20	21	7.15	150.15	0.375

*$P = \gamma S^2$, $P = VI$

Table 6. Partial Derivative Matrix of Temperature Change Due to Changes in Electrical Heater Power for the OT Position of the Pressure Vessel Capsule. The units are °C per watt. Data for determining electrical heater power from variac setting are listed below the partial derivative matrix.

Thermocouple	Variac Number									
	11	12	13	14	15	16	17	18	19	20
21	.0333	.0698	.0991	.194	.202	.0605	.0617	.0979	.147	.148
22	.0388	.0756	.119	.194	.182	.0605	.0669	.111	.141	.135
23	.0333	.0863	.125	.139	.208	.0571	.0747	.117	.117	.153
24	.0401	.1054	.143	.114	.179	.0687	.0935	.136	.104	.141
25	.0367	.1270	.125	.0877	.205	.0707	.1142	.129	.0979	.158
26	.0299	.1670	.123	.0747	.168	.0741	.1364	.127	.0824	.143
27	.0286	.1810	.096	.0633	.191	.0687	.1461	.112	.0789	.155
28	.0619	.0590	.096	.236	.0845	.103	.0759	.119	.191	.0966
29	.0667	.0590	.103	.252	.0877	.0986	.0701	.114	.173	.0918
30	.0667	.1219	.159	.106	.0928	.0952	.1045	.143	.0979	.0871
31	.0701	.1251	.170	.111	.0973	.0918	.1032	.134	.0923	.0850
32	.1340*	.2463	.112	.0801	.102	.0918	.1759	.108	.0683	.0837
33	.0714	.2559	.105	.0694	.0909	.0918	.1727	.114	.0683	.0898
34	.1592	.0603	.0875	.166	.0615	.147	.0636	.0968	.130	.0619
35	.1408	.0787	.112	.173	.0755	.141	.0669	.105	.127	.0605
36	.1626	.0819	.111	.127	.0583	.156	.0812	.115	.113	.0619
37	.1361	.1022	.130	.0984	.0679	.156	.0968	.131	.108	.0687
38	.1537	.1213	.108	.0786	.0499	.168	.1162	.121	.0901	.0707
39	.1340	.1556	.103	.0633	.0608	.151	.1403	.117	.0817	.0721
40	.1456	.1651	.0736	.0488	.0519	.174	.1545	.113	.0831	.0735

Table 6. Partial Derivative of Temperature Changes (Cont'd)

Variac	Setting(s)	V	I	Power (P)**	γ**
11	15.2	21	7	147	0.64
12	17.5	22.5	7	157.5	0.51
13	17	23.5	7	164.5	0.57
14	15	19	6.9	131.1	0.58
15	9	22	7.1	156.2	1.93
16	16	21	7	147	0.57
17	17	22	7	154	0.53
18	19	24.5	7	171.5	0.48
19	15.1	20	7.1	142	0.62
20	7.5	21	7	147	2.61

*Bad thermocouple reading
**$P = \gamma S^2$, $P = VI$

Table 7. Partial Derivative Matrix of Temperature Changes Due to Changes in Electrical Heater Power for the 1/4 T Position of the Pressure Vessel Capsule. The units are °C per watt. Data for determining electrical heater power and the conversion factor (γ) for computing heater power from variac setting are listed below the partial derivative matrix.

Thermocouple	Variac Number									
	21	22	23	24	25	26	27	28	29	30
41	.0204	.0481	.0715	.186	.150	.0713	.0692	.104	.148	.169
42	.0407	.0651	.0823	.189	.140	.0663	.0692	.111	.144	.149
43	.0426	.0763	.0900	.153	.169	.0556	.0734	.112	.113	.159
44	.0611	.0980	.113	.146	.158	.0524	.0792	.123	.0896	.133
45	.0426	.1180	.0977	.111	.166	.0556	.0992	.112	.0812	.155
46	.0426	.1397	.0874	.0919	.137	.0663	.1309	.118	.0766	.145
47	.0315	.1555	.0715	.0830	.156	.0631	.1367	.103	.0766	.155
48	.0741	.0622	.0699	.236	.0803	.0953	.0663	.109	.189	.0970
49	.0815	.0569	.0761	.246	.0803	.0928	.0634	.108	.182	.0929
50	.0796	.0998	.105	.113	.0792	.0928	.1015	.146	.0981	.0929
51	.0815	.1015	.111	.109	.0763	.0959	.1015	.143	.0961	.0929
52	.0815	.1831	.0736	.0768	.0804	.0959	.1790	.112	.0759	.0963
53	.0843	.1960	.0772	.0786	.0804	.0978	.1737	.112	.0740	.0963
54	.1630	.0558	.0648	.174	.0575	.150	.0646	.0951	.133	.0699
55	.1491	.0628	.0772	.177	.0622	.136	.0657	.104	.131	.0685
56	.1833	.0745	.0838	.142	.0604	.155	.0745	.105	.106	.0651
57	.1556	.0945	.0972	.122	.0604	.138	.0874	.128	.0948	.0719
58	.1806	.1074	.0874	.100	.0593	.157	.1015	.114	.0825	.0699
59	.1519	.1356	.0849	.0893	.0646	.148	.1303	.114	.0773	.0733
60	.1741	.1444	.0684	.0786	.0593	.158	.1373	.101	.0727	.0719

Table 7. Partial Derivative Matrix of Temperature Changes (Cont'd)

Variac	Setting(s)	V	I	Power (P)*	γ*
21	14.2	15	7.2	108	0.54
22	17	24	7.1	170.4	0.59
23	20	27	7.2	194.4	0.49
24	15	16	7	112	0.50
25	9	24	7.1	170.4	2.10
26	15	22	7.2	158.4	0.70
27	17	24	7.1	170.4	0.59
28	18	26	7.2	187.2	0.58
29	16	22	7	154	0.60
30	9	22	6.7	147.4	1.82

*$P = \gamma S^2$, $P = VI$

Table 8. Partial Derivative Matrix of Temperature Changes Due to Changes in Electrical Heater Power for the 1/2 T Position of the Pressure Vessel Capsule. The units are °C per watt. Data for determining electrical heater power and the conversion factor (γ) for computing heater power from variac setting are listed below the partial derivative matrix.

Thermo-couple	Variac Number									
	31	32	33	34	35	36	37	38	39	40
61	.0370	.0528	.0633	.116	.129	.0675	.0687	.104	.147	.139
62	.0454	.0611	.0576	.116	.111	.0675	.0687	.111	.141	.120
63	.0324	.0611	.0711	.0889	.124	.0675	.0804	.120	.120	.136
64	.0389	.0728	.0833	.0781	.108	.0733	.0886	.135	.103	.122
65	.0296	.0800	.0728	.0627	.129	.0565	.1004	.114	.0883	.134
66	.0343	.0989	.0689	.0563	.106	.0721	.1273	.122	.0805	.119
67	.0454*	.0611*	.0576*	.116*	.111*	.0675*	.0687*	.111*	.141*	.120*
68	.0593	.0500	.0594	.111	.0653	.0929	.0704	.107	.185	.0793
69	.0491	.0467	.0567	.122	.0653	.0968	.0792	.115	.179	.0868
70	.0537	.0833	.0783	.067	.0734	.0935	.1009	.141	.0941	.0839
71	.0583	.0833	.0889	.0659	.0734	.0935	.0992	.142	.0955	.0828
72	.0630	.1333	.0633	.0595	.0775	.0922	.1766	.112	.0794	.0781
73	.0611	.1483	.0661	.0486	.0793	.103	.1755	.114	.0734	.0839
74	.1102	.0522	.0483	.0967	.0549	.144	.0710	.0994	.135	.0642
75	.0880	.0522	.0528	.0909	.0538	.138	.0792	.112	.135	.0683
76	.1102	.0589	.0622	.0736	.0549	.154	.0822	.113	.109	.0642
77	.0880	.0672	.0744	.0704	.0567	.138	.0910	.131	.0974	.0642
78	.1241	.0817	.0672	.0595	.0527	.151	.1021	.114	.0877	.0602
79	.0963	.1011	.0606	.0563	.0579	.135	.1268	.118	.0812	.0700
80	.1167	.0928	.0472	.0409	.0451	.151	.1238	.109	.0799	.0625

Table 8. Partial Derivative Matrix of Temperature Changes (Cont'd)

Variac	Setting(s)	V	I	Power (P)**	γ**
31	15.5	15	7.2	108	0.45
32	19	25	7.2	180	0.50
33	18	25	7.2	180	0.56
34	16	22	7.1	156.2	0.61
35	9.5	24	7.2	172.8	1.91
36	16.7	22.0	7.0	154	0.55
37	18	24	7.1	170.4	0.53
38	21	26	7	182	0.41
39	15.8	22	7	154	0.62
40	9.5	24	7.2	172.8	1.91

*Bad thermocouple readings

**$P = \gamma S^2$, $P = VI$

Table 9. Average Temperature Changes Due to Changes in Reactor Power for each Set of Irradiation Specimens in Units of °C Per MW

Position	Average Temperature Change (°C/MW)
Surveillance Capsule	5.56
Pressure Vessel Capsule	
OT	6.64
1/4T	6.52
1/2T	6.26

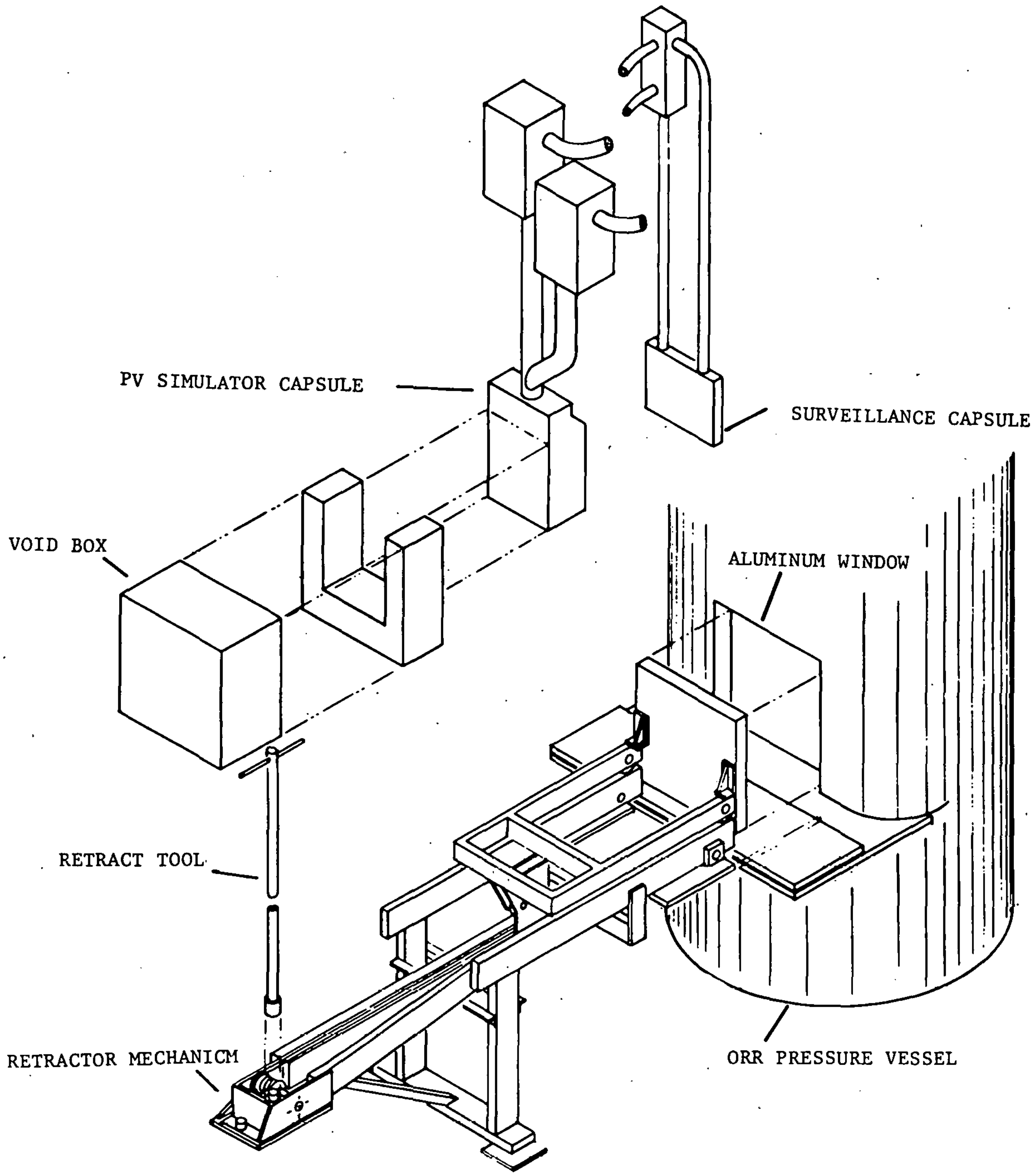

Fig. 1. LWR Metallurgical Pressure Vessel Benchmark Facility (PSF).

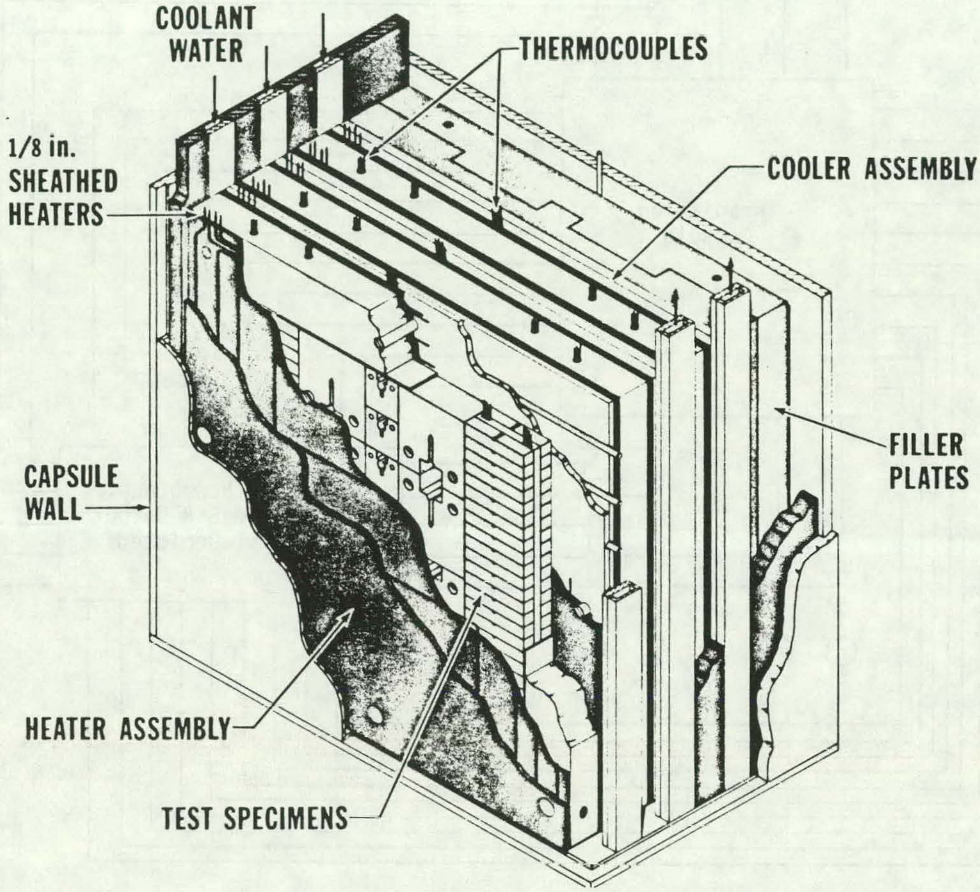

Fig. 2. PSF Instrumented Irradiation Capsule (Assembled).

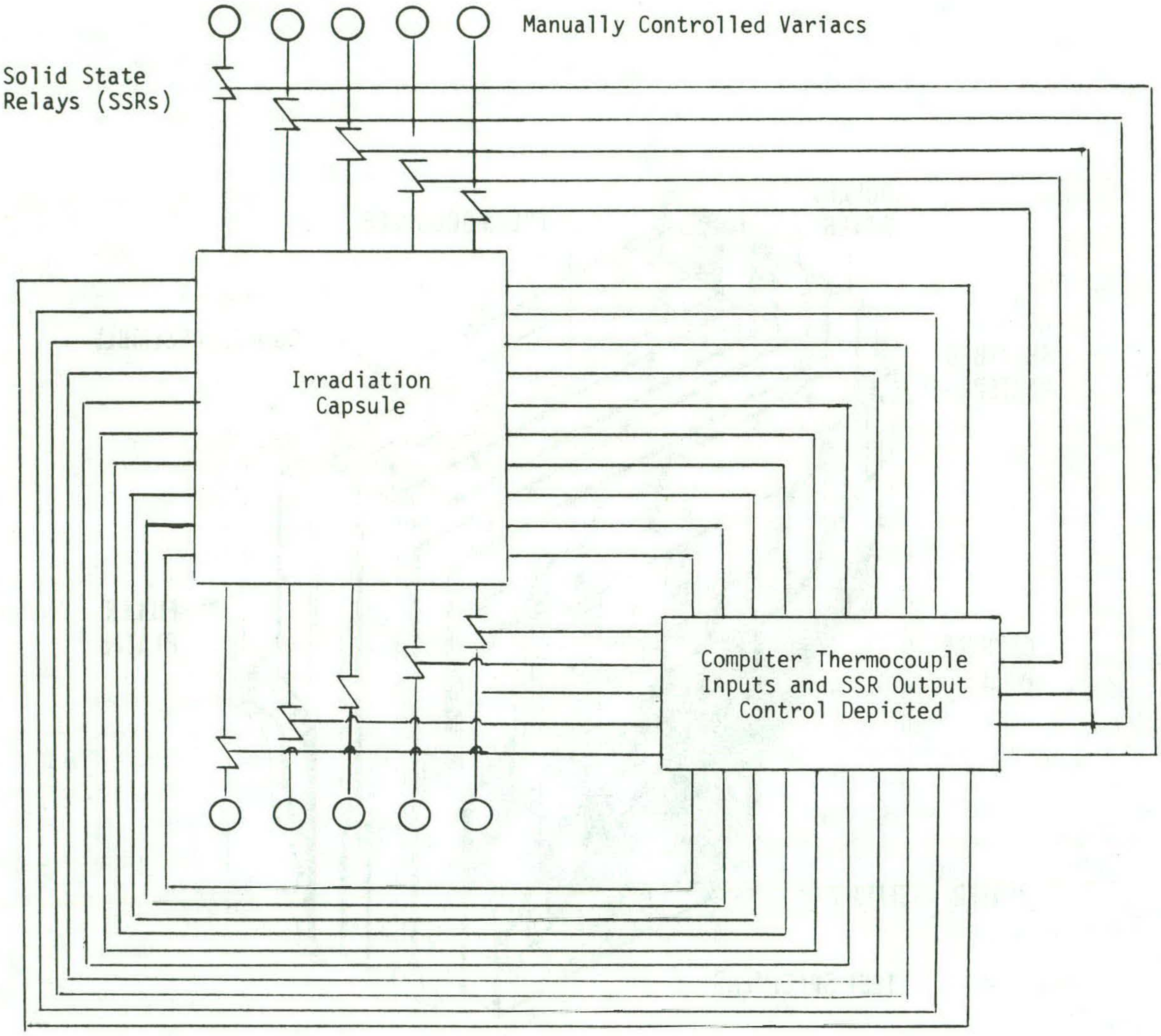

Fig. 3. Schematic Diagram of an Irradiation Capsule with Thermocouple Outputs and Heater Control Depicted. Note that the computer controls the firing of solid-state relays between variacs and electrical heaters.

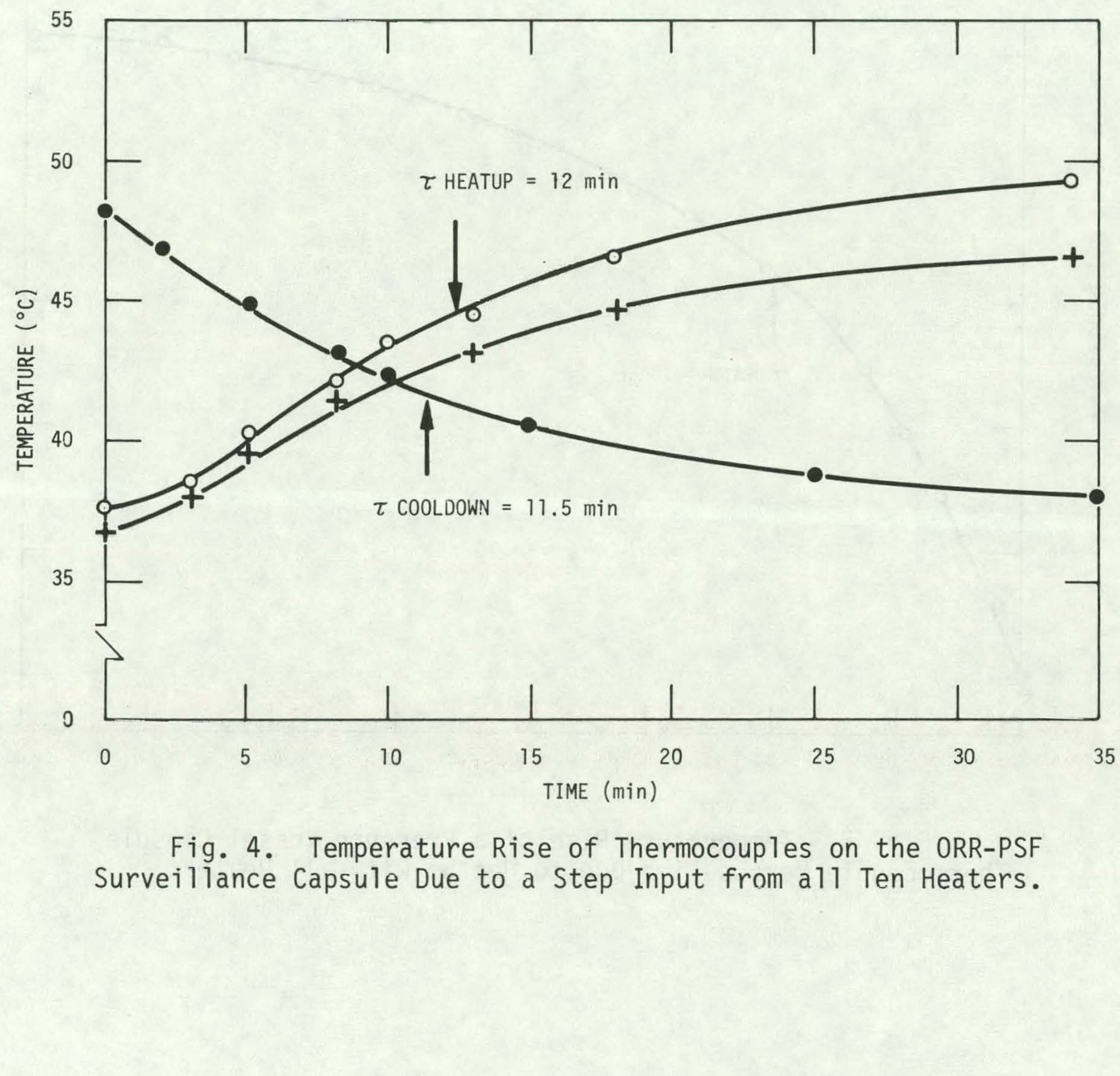

Fig. 4. Temperature Rise of Thermocouples on the ORR-PSF Surveillance Capsule Due to a Step Input from all Ten Heaters.

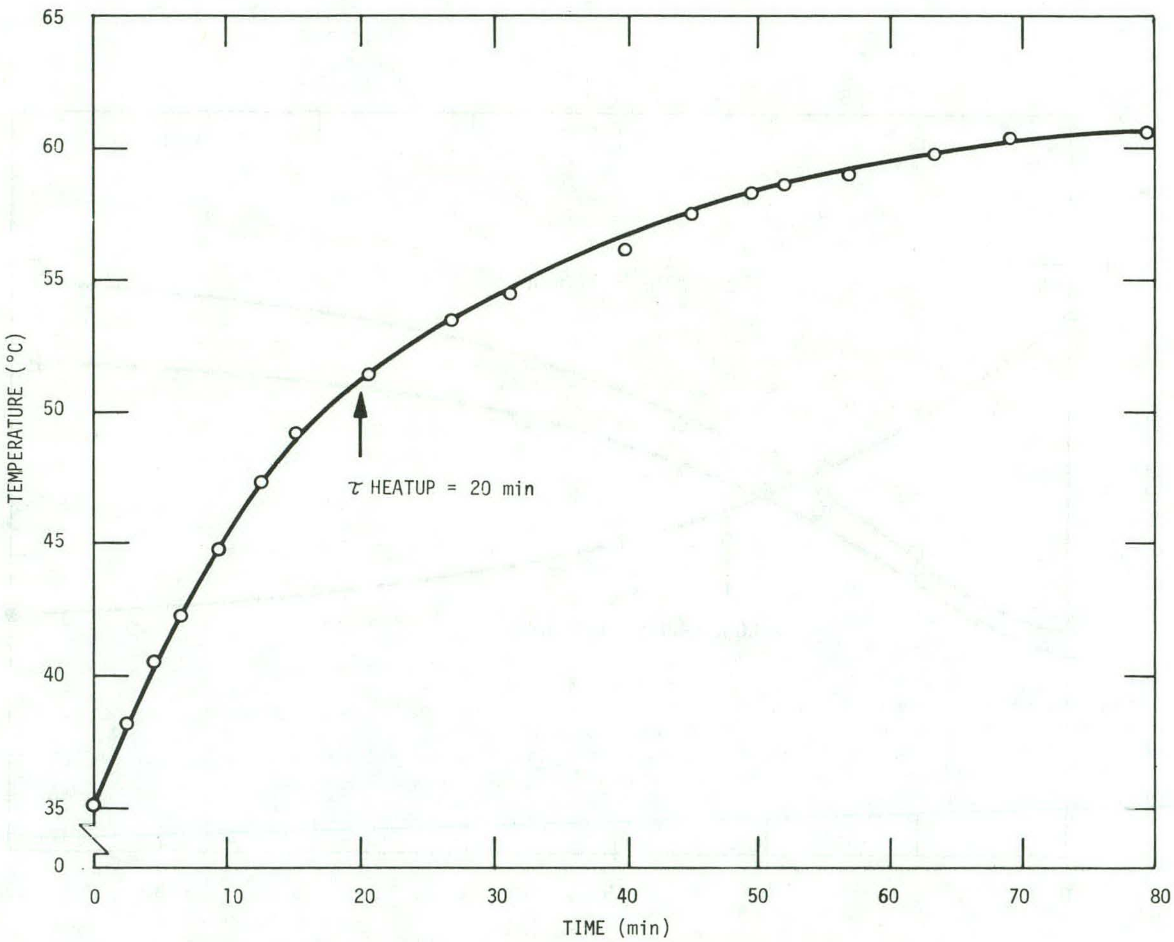

Fig. 5. Temperature Rise of a Pressure Vessel Capsule Thermocouple Versus Time Due to Heatup with all Heaters.

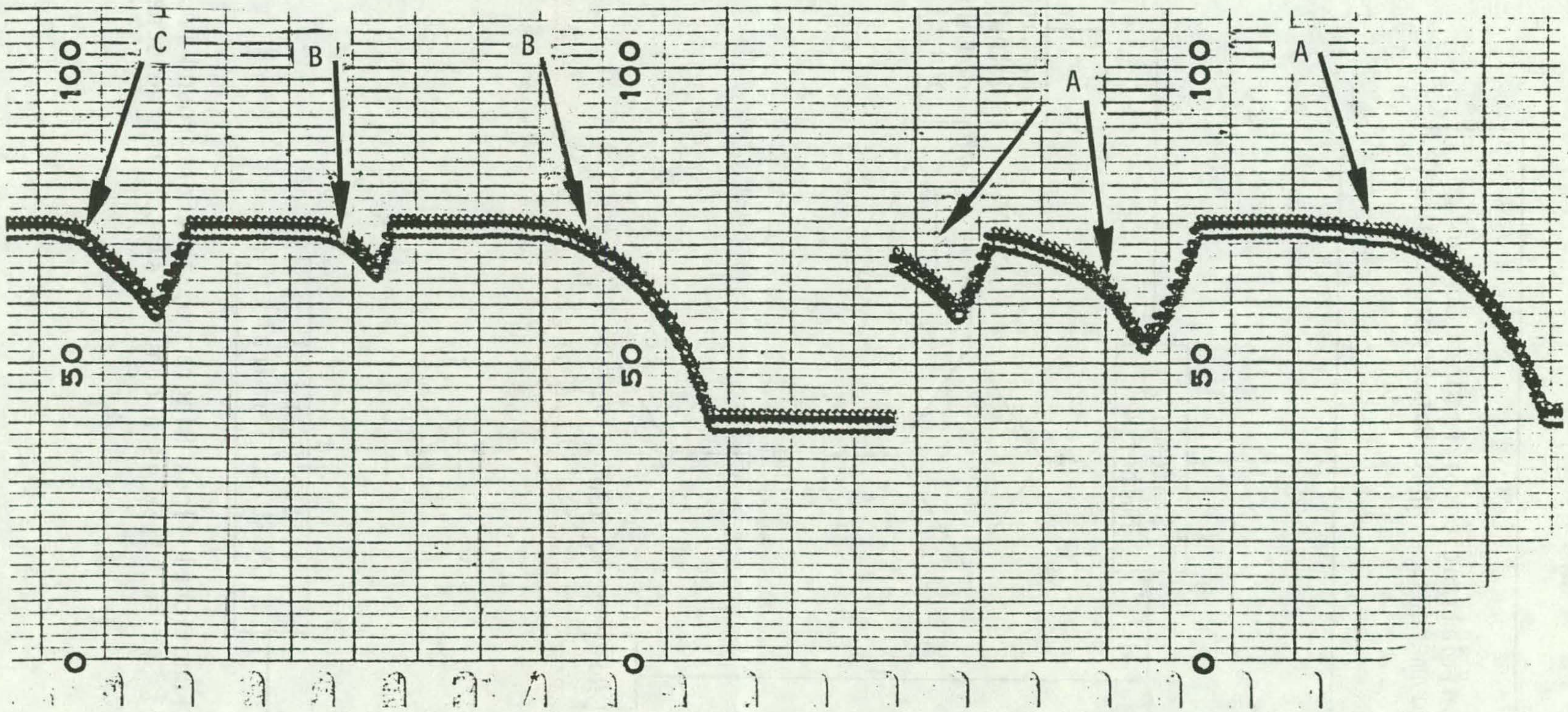

Fig. 6. Example of Several Algorithm Tests: A) Proportional Control, B) Integral Control, and C) Average Temperature Control.

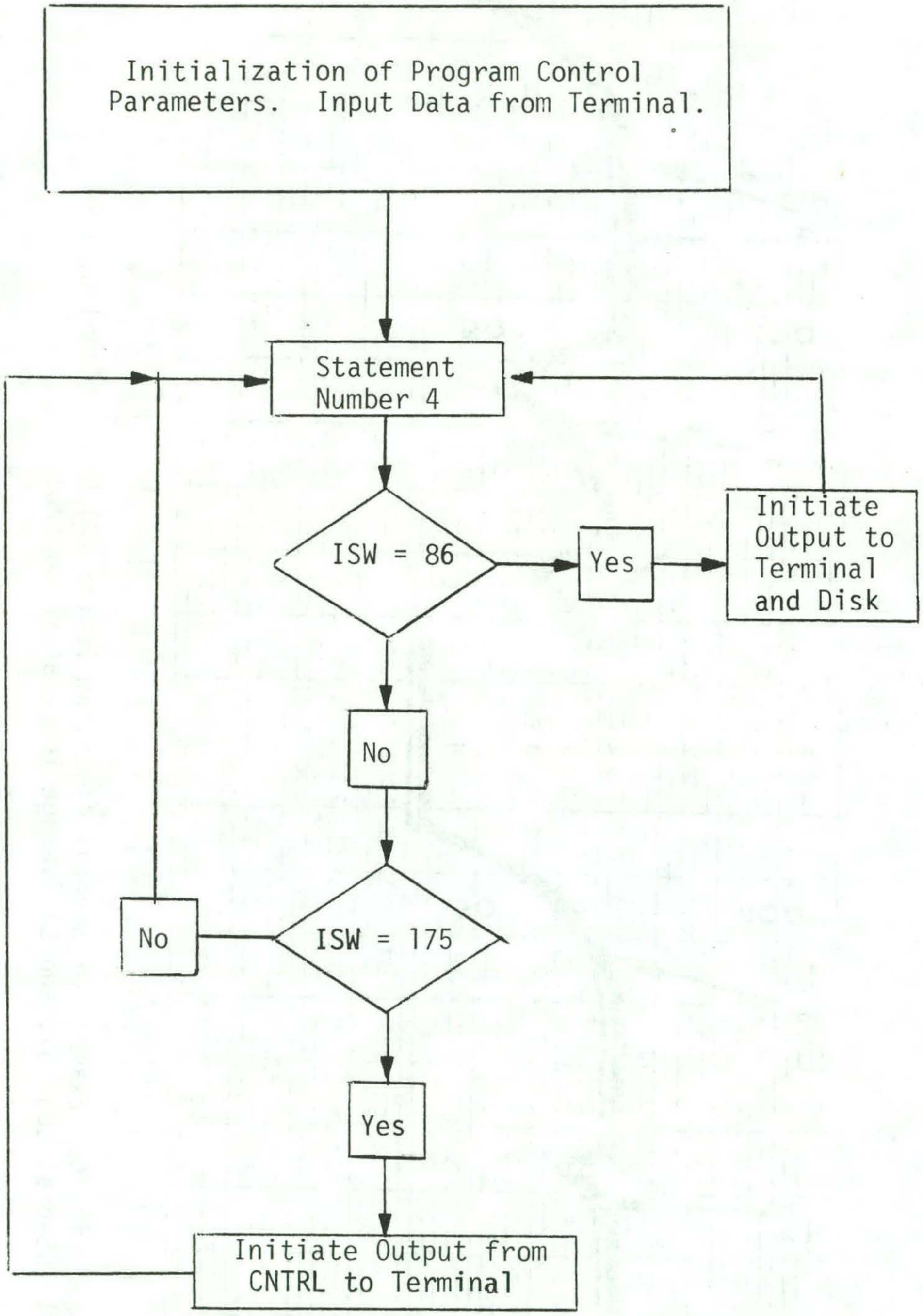

Fig. 7. Functional Block Diagram of the Foreground Program of the Process Control System. ISW is a control switch in the scheduling algorithm.

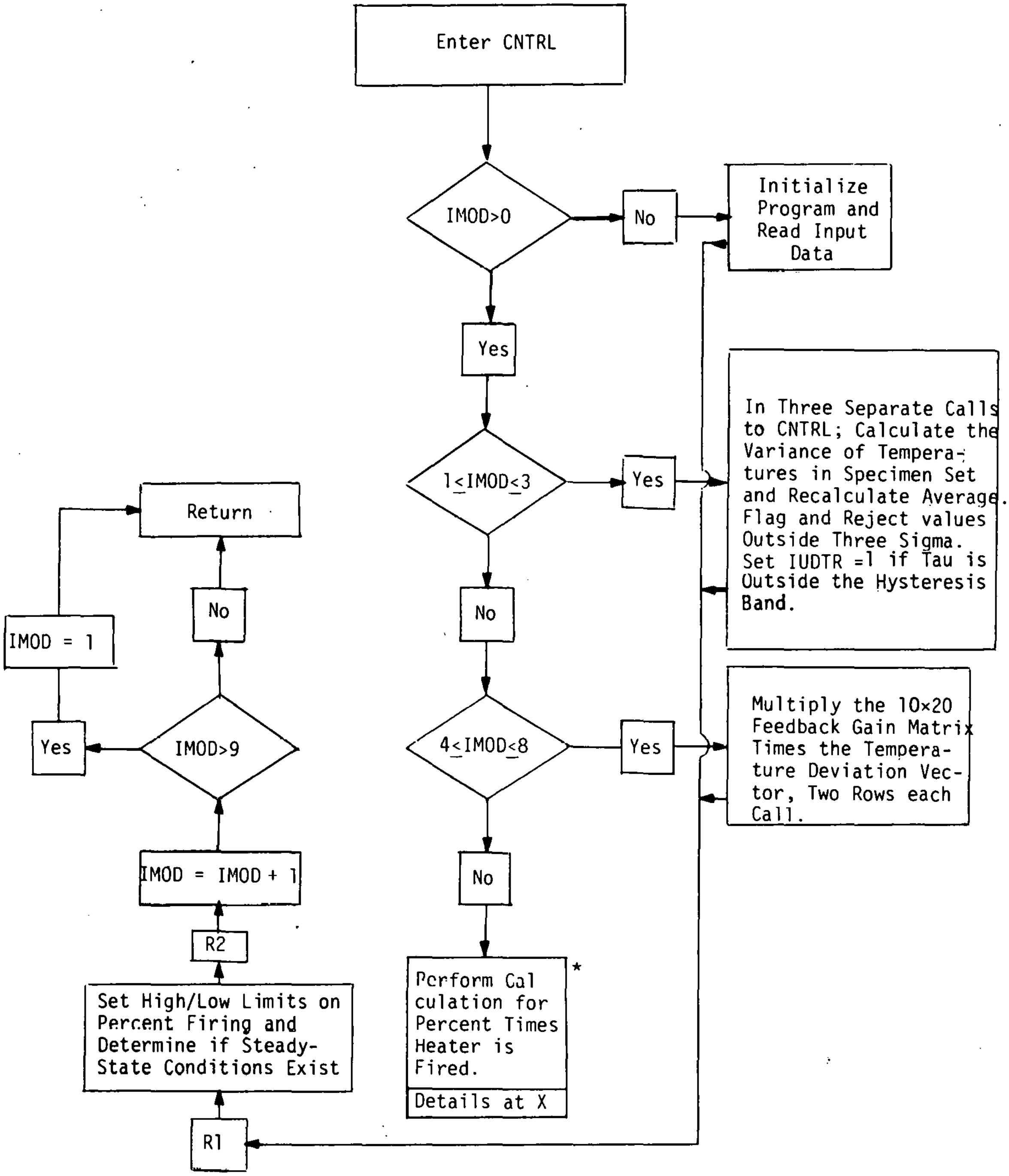

Fig. 8. Overall Block Diagram of the Subroutine for Control of the Electrical Heaters. Details on the block marked with the asterisk are shown in Fig. 9 and in the listing.

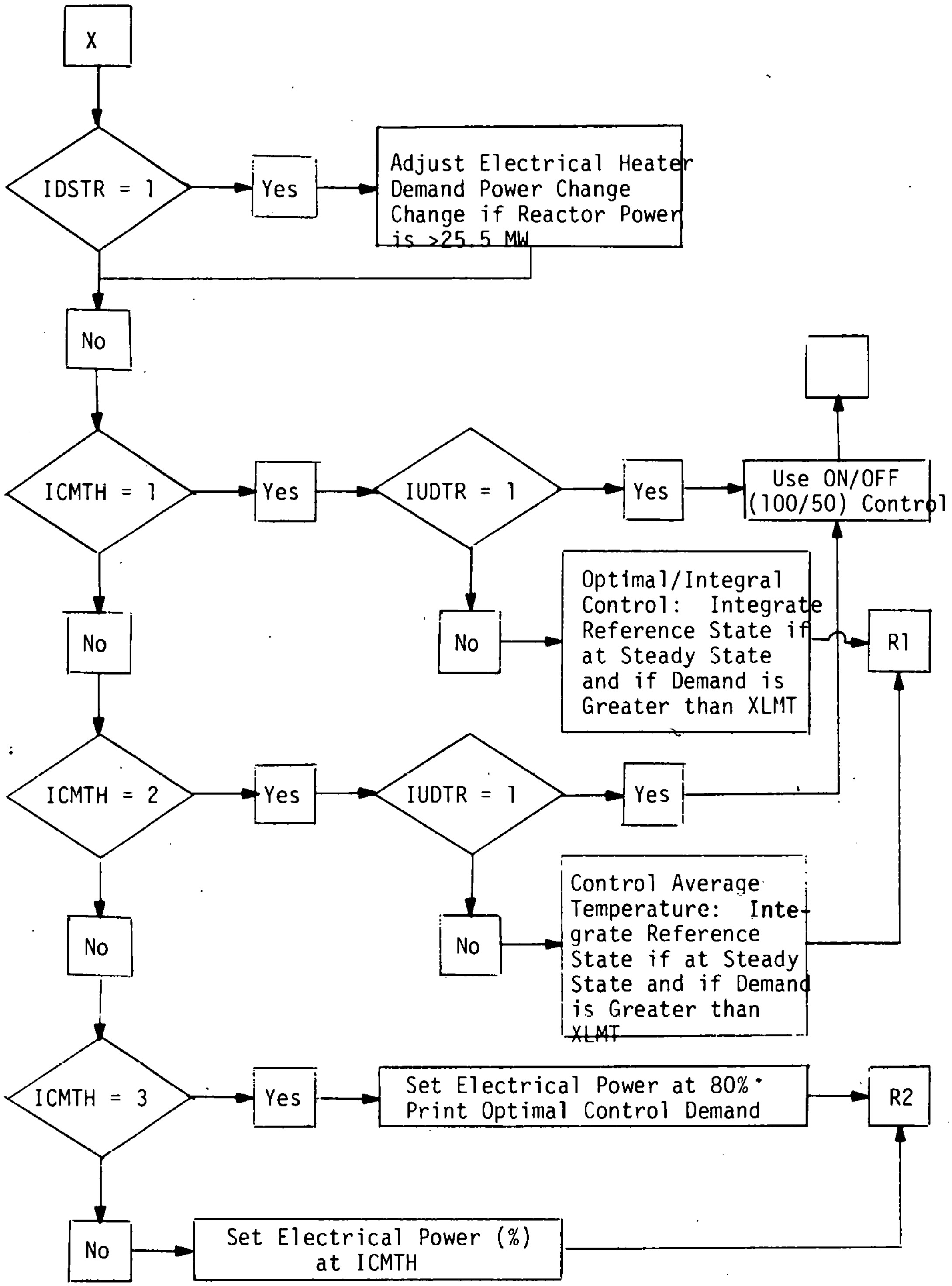

Fig. 9. Block Diagram of the Section of Subroutine CNTRL which Calculates the Percent of Time Electrical Heaters are on.

APPENDIX

```
FORTRAN IV G LEVEL  21                  MAIN                DATE = 80101          15/57/32

                 IMPLICIT REAL*8(A-H.O-Z)
                 COMPLEX*16 WZ(30).ZZ(30.30)
                 DIMENSION A(30.30).B(30.30).C(30.30).Q(30.30).R(30.30).F(30.30).
                1 G(30.30).DIR(30.30).RIV(30.30).WK1(30.30).WK2(30.30).WK3(30.30).
                2 ATPS(30.30).AIVT(30.30).U(30.30).V(30.30).W(30.30).WKAR(3500).
                3 BTS(30.30)
                 DIMENSION FCOF(30.30).P(30.30).RID(30.30).PSAV(30.30).
                1 FTPS(30.30).VTPS(30.30).GSAV(30.30)
                 DIMENSION ITITLE(5)
                 DIMENSION DVMT(  1.  1).SP(475).GBR(30.30)
                 DIMENSION FMT(9)
                 EXTERNAL RCF2
                 NC=0
                 IOPT=3
                 IA=30
                 IB=475
                 ITST=1
          C***IF IDORC .NE. 0 THE DISCRETE TIME EQS ARE SOLVED
          C***IF IDORC .GT. 0 THE CONTINUOUR TIME EQS ARE FIRST DISCRETIZED
          C***IF IBDEL .NE. 0 THE SYSTEM INPUT MATRIX IS MODIFIED BY B=-AB
                 READ(5.1000)NN.NP.NQ.NITM.EPCG.IDORC.TAU.IBDEL
            1000 FORMAT(4I5.E10.3.I5.E10.3.I5)
                 WRITE(6.1014)NN.NP.NQ.NITM.EPCG.IDORC.TAU.IBDEL
            1014 FORMAT('1'.' NN ='.I4.' NP ='.I4.' NQ ='.I4.' NITM ='.I4.' EPCG ='
               1.E10.3.' IDORC ='.I5.' TAU = '.E10.3.' IBDEL = '.I4)
                 READ(5.1001)FMT
            1001 FORMAT(18A4)
                 CALL USRDM(NN.NN.FMT.IA.A)
                 WRITE(6.1002)
            1002 FORMAT('0'.' THE REFERENCE SYSTEM MATRIX')
                 CALL USWFM(ITITLE.NC.A.IA.NN.NN.IOPT)
                 CALL USRDM(NN.NP.FMT.IA.B)
                 WRITE(6.1003)
            1003 FORMAT('0'.' THE REFERENCE SYSTEM INPUT MATRIX')
                 CALL USWFM(ITITLE.NC.B.IA.NN.NP.IOPT)
                 IF(IBDEL.EQ.0)GO TO 7
                 CALL VMULFF(A.B.NN.NN.NP.IA.IA.WK1.IA.IER)
                 DO 5 I=1.NN
                 DO 5 J=1.NP
            5    B(I.J)=-WK1(I.J)
                 WRITE(6.1201)
            1201 FORMAT(' THE B MATRIX WAS MODIFIED BY B=-AB')
                 CALL USWFM(ITITLE.NC.B.IA.NN.NP.IOPT)
             7   CONTINUE
                 CALL USRDM(NQ.NN.FMT.IA.C)
                 WRITE(6.1004)
            1004 FORMAT('0'.' THE REFERENCE SYSTEM OUTPUT MATREX')
                 CALL USWFM(ITITLE.NC.C.IA.NQ.NN.IOPT)
                 CALL USRDM(NN.NN.FMT.IA.Q)
                 WRITE(6.1005)
            1005 FORMAT('0'.' THE SYSTEM MODE WEIGHTING MATRIX')
                 CALL USWFM(ITITLE.NC.Q.IA.NN.NN.IOPT)
                 CALL USRDM(NP.NP.FMT.IA.R)
                 WRITE(6.1006)
            1006 FORMAT('0'.' THE SYSTEM CONTROL WEIGHTING MATRIX')
                 CALL USWFM(ITITLE.NC.R.IA.NP.NP.IOPT)
          C COMPUTE THE INVERSE OF R
                 IDGT=8
```

A.1. Listing of a Computer Program for Solving the Matrix Riccati Equation.

```
FORTRAN IV G LEVEL  21                  MAIN                DATE = 80101           15/57/32
               CALL LINV2F(R,NP,IA,RIV,IDGT,WKAR,IER)
               IF(IDORC.LT.0)GO TO 63
         C****CALL DSCTIZ TO DISCRITIZE THE CONTINUOUS TIME DIFFERENTIAL EQS.
               EPX=1.0E-5
               ITMX=100
               CALL DSCTIZ(A,WK1,WK2,EPX,TAU,IA,NN,ITMX,U,V)
               CALL VMULFF(V,B,NN,NN,NP,IA,IA,WK1,IA,IER)
               DO 58 I=1,NN
               DO 58 J=1,NN
               A(I,J)=U(I,J)
            58 B(I,J)=WK1(I,J)
               WRITE(6,1100)
          1100  FORMAT('  DISCRITIZED SYSTEM MATRIX')
               CALL USWFM(ITITLE,NC,A,IA,NN,NN,IOPT)
               WRITE(6,1120)
          1120 FORMAT(' DISCRITIZED SYSTEM INPUT MATRIX')
               CALL USWFM(ITITLE,NC,B,IA,NN,NP,IOPT)
            63 CONTINUE
         C***COMPUTE A TRANSPOSE, B TRANSPOSE AND INITIALIZE VARIABLES
               DO 10 I=1,NN
               DO 10 J=1,NN
            10 ATPS(I,J)=A(J,I)
               DO 15 I=1,NN
               DO 15 J=1,NN
               P(I,J)=0.0
               PSAV(I,J)=0.0
               GSAV(I,J)=0.0
         15    G(I,J)=0.0
               DO 30 I=1,NP
               DO 30 J=1,NN
            30 BTS(I,J)=B(J,I)
         C****START ITERATIONS
               XNRL=0.0
               XTM=1.0
               IT=0
          20   IT=IT+1
               IDGT=0
         C***CALCULATE THE SEARCH DIRECTION AND THE RESIDUAL NORM
               GAM=0.0
         C****SET ARGUMENTS
               XZR=RCF1(NN,NP,IA,G,A,B,Q,RIV,WK1,WK2,WK3,IDORC,P,BTS ,R,FCOF,
              1 IDGT,WKAR,F,FTPS,V,VTPS,DIR,ATPS,GSAV,PSAV,RID)
               XNRM=RCF2(GAM)
               WRITE(6,1007)XNRM
          1007 FORMAT('0',' THE RICCATI EQUATION NORM IS ',E12.5)
               IF(XNRM.LT.EPCG)GO TO 50
               IF(DABS((XNRM-XNRL)/XNRM).LT.EPCG)GO TO 50
               IF(XNRM/XTM.LT.EPCG)GO TO 50
               XNRL=XNRM
         C***CALCULATE A NEW SEARCH DIRECTION
               DO 22 I=1,NN
               DO 22 J=1,NN
           22  DIR(I,J)=0.5*(RID(I,J)+RID(J,I))
         C***CONDUCT A LINE SEARCH FOR THE OPTIMUN STEP SIZE
               XMIN=0.5
               TOL=0.1
               ALOW=-1.0
               BHIG=1.5
```

A.1. Listing of a Computer Program (Cont'd).

```
FORTRAN IV G LEVEL  21                MAIN                DATE = 80101          15/57/32
              C****SET ARGUMENTS
                   XZR=RCF1(NN,NP,IA,G,A,B,Q,RIV,WK1,WK2,WK3,IDORC,P,BTS ,R,FCOF,
                  1 IDGT,WKAR,F,FTPS,V,VTPS,DIR,ATPS,GSAV,PSAV,RID)
                   IF(ITST.EQ.1)GO TO 38
                   CALL ZXGSN(RCF2,ALOW,BHIG,TOL,XMIN,IER)
                   GAM=XMIN
                   WRITE(6,1212)GAM
              1212 FORMAT('  THE LINE SEARCH PARAMETER = ',E12.5)
                   GO TO 39
                38 CONTINUE
                    GAM=1.0
               39  CONTINUE
                   DO 40 I=1,NN
                   DO 40 J=1,NN
                   PSAV(I,J)=PSAV(I,J)+DIR(I,J)*GAM
               40  GSAV(I,J)=GSAV(I,J)+DIR(I,J)*GAM
                   XTM=RCF1(NN,NP,IA,G,A,B,Q,RIV,WK1,WK2,WK3,IDORC,P,BTS ,R,FCOF,
                  1 IDGT,WKAR,F,FTPS,V,VTPS,DIR,ATPS,GSAV,PSAV,RID)
                   IF(IT.LE.NITM)GO TO 20
                50 CONTINUE
                   IF(IDORC.NE.0)GO TO 64
                   CALL VMULFF(BTS,G,NP,NN,NN,IA,IA,WK1,IA,IER)
                   CALL VMULFF(RIV,WK1,NP,NP,NN,IA,IA,WK2,IA,IER)
                   DO 60 I=1,NP
                   DO 60 J=1,NN
                60 F(I,J)=-WK2(I,J)
                64 CONTINUE
              C PRINT RESULTS
                   WRITE(6,1008)
              1008 FORMAT('0',' THE RICCATI EQUATION UNKNOWN MATRIX')
                   IF(IDORC.EQ.0)CALL USWFM(ITITLE,NC,GSAV,IA,NN,NN,IOPT)
                   IF(IDORC.NE.0)CALL USWFM(ITITLE,NC,PSAV,IA,NN,NN,IOPT)
                   WRITE(6,1009)
              1009 FORMAT('0',' THE SYSTEM GAIN MATRIX')
                   CALL USWFM(ITITLE,NC,F,IA,NP,NN,IOPT)
                   IF(IT.GE.NITM)GO TO 65
                   DO 61 I=1,NP
                   WRITE(7,1402)(F(I,J),J=1,NN)
              1402 FORMAT(10F8.3)
               61  CONTINUE
               65  CONTINUE
                   CALL VMULFF(B,F,NN,NP,NN,IA,IA,WK1,IA,IER)
                   DO 70 I=1,NN
                   DO 70 J=1,NN
                70 WK1(I,J)=A(I,J)+WK1(I,J)
                   IJOB=0
                   CALL EIGRF(WK1,NN,IA,IJOB,WZ,ZZ,IA,WKAR,IER)
                   WRITE(6,1010)(WZ(I),I=1,NN)
              1010 FORMAT('0',' THE CLOSED LOOP EIGENVALUES '/('0',10X,2E12.5))
                   IJOB=0
                   CALL EIGRF(A,NN,IA,IJOB,WZ,ZZ,IA,WKAR,IER)
                   WRITE(6,1011)(WZ(I),I=1,NN)
              1011 FORMAT('0',' THE REFERENCE SYSTEM EIGENVALUES '/('0',10X,2E12.5))
                   STOP
                   END
```

A.1. Listing of a Computer Program (Cont'd).

```
FORTRAN IV G LEVEL  21                  MAIN                DATE = 80101          15/57/32

                C****SET ARGUMENTS
                     XZR=RCF1(NN.NP.IA.G.A.B.Q.RIV.WK1.WK2.WK3.IDORC.P.BTS .R.FCOF.
                    1 IDGT.WKAR.F.FTPS.V.VTPS.DIR.ATPS.GSAV.PSAV.RID)
                     IF(ITST.EQ.1)GO TO 38
                     CALL ZXGSN(RCF2.ALOW.BHIG.TOL.XMIN.IER)
                     GAM=XMIN
                     WRITE(6.1212)GAM
                1212 FORMAT('  THE LINE SEARCH PARAMETER = '.E12.5)
                     GO TO 39
                  38 CONTINUE
                      GAM=1.0
                 39  CONTINUE
                     DO 40 I=1.NN
                     DO 40 J=1.NN
                     PSAV(I.J)=PSAV(I.J)+DIR(I.J)*GAM
                 40  GSAV(I.J)=GSAV(I.J)+DIR(I.J)*GAM
                     XTM=RCF1(NN.NP.IA.G.A.B.Q.RIV.WK1.WK2.WK3.IDORC.P.BTS .R.FCOF.
                    1 IDGT.WKAR.F.FTPS.V.VTPS.DIR.ATPS.GSAV.PSAV.RID)
                     IF(IT.LE.NITM)GO TO 20
                  50 CONTINUE
                     IF(IDORC.NE.0)GO TO 64
                     CALL VMULFF(BTS.G.NP.NN.NN.IA.IA.WK1.IA.IER)
                     CALL VMULFF(RIV.WK1.NP.NP.NN.IA.IA.WK2.IA.IER)
                     DO 60 I=1.NP
                     DO 60 J=1.NN
                  60 F(I.J)=-WK2(I.J)
                  64 CONTINUE
                C PRINT RESULTS
                     WRITE(6.1008)
                1008 FORMAT('0'.' THE RICCATI EQUATION UNKNOWN MATRIX')
                     IF(IDORC.EQ.0)CALL USWFM(ITITLE.NC.GSAV.IA.NN.NN.IOPT)
                     IF(IDORC.NE.0)CALL USWFM(ITITLE.NC.PSAV.IA.NN.NN.IOPT)
                     WRITE(6.1009)
                1009 FORMAT('0'.' THE SYSTEM GAIN MATRIX')
                     CALL USWFM(ITITLE.NC.F.IA.NP.NN.IOPT)
                     IF(IT.GE.NITM)GO TO 65
                     DO 61 I=1.NP
                     WRITE(7.1402)(F(I.J).J=1.NN)
                1402 FORMAT(10F8.3)
                 61  CONTINUE
                 65  CONTINUE
                     CALL VMULFF(B.F.NN.NP.NN.IA.IA.WK1.IA.IER)
                     DO 70 I=1.NN
                     DO 70 J=1.NN
                  70 WK1(I.J)=A(I.J)+WK1(I.J)
                     IJOB=0
                     CALL EIGRF(WK1.NN.IA.IJOB.WZ.ZZ.IA.WKAR.IER)
                     WRITE(6.1010)(WZ(I).I=1.NN)
                1010 FORMAT('0'.' THE CLOSED LOOP EIGENVALUES '/('0'.10X.2E12.5))
                     IJOB=0
                     CALL EIGRF(A.NN.IA.IJOB.WZ.ZZ.IA.WKAR.IER)
                     WRITE(6.1011)(WZ(I).I=1.NN)
                1011 FORMAT('0'.' THE REFERENCE SYSTEM EIGENVALUES '/('0'.10X.2E12.5))
                     STOP
                     END
```

A.1. Listing of a Computer Program (Cont'd).

```
FORTRAN IV G LEVEL  21                  RCF1               DATE = 80101          15/57/32

             REAL FUNCTION RCF1*8(NN,NP,IA,G,A,B,Q,RIV,WK1,WK2,WK3,IDORC,P,
            1BTPS,R,FCOF,IDGT,WKAR,F,FTPS,V,VTPS,DIR,ATPS,GSAV,PSAV,RID)
             IMPLICIT REAL*8(A-H,O-Z)
             DIMENSION G(IA,1),A(IA,1),Q(IA,1),RIV(IA,1),WK1(IA,1),WK2(IA,1),
            1 WK3(IA,1),P(IA,1),BTPS(IA,1),R(IA,1),FCOF(IA,1),WKAR(1),F(IA,1),
            2 FTPS(IA,1),V(IA,1),VTPS(IA,1),DIR(IA,1),ATPS(IA,1),GSAV(IA,1),
            3 PSAV(IA,1),RID(IA,1),B(IA,1)
             IF(IDORC.NE.0)CALL VNRMFI(PSAV,NN,IA,XTMP)
             IF(IDORC.EQ.0)CALL VNRMFI(GSAV,NN,IA,XTMP)
             RCF1=XTMP
             RETURN
             ENTRY RCF2(GAM)
             IF(IDORC.NE.0)GO TO 30
             DO 10 I=1,NN
             DO 10 J=1,NN
       10    G(I,J)=GSAV(I,J)+DIR(I,J)*GAM
             CALL VMULFF(G,A,NN,NN,NN,IA,IA,WK1,IA,IER)
             CALL VMULFF(ATPS,G,NN,NN,NN,IA,IA,WK2,IA,IER)
             CALL VMULFF(BTPS,G,NP,NN,NN,IA,IA,WK3,IA,IER)
             CALL VMULFF(RIV,WK3,NP,NP,NN,IA,IA,P,IA,IER)
             CALL VMULFF(B,P,NN,NP,NN,IA,IA,F,IA,IER)
             CALL VMULFF(G,F,NN,NN,NN,IA,IA,P,IA,IER)
             DO 20 I=1,NN
             DO 20 J=1,NN
       20    RID(I,J)=-Q(I,J)-WK1(I,J)-WK2(I,J)+P(I,J)
             GO TO 50
       30    CONTINUE
             DO 40 I=1,NN
             DO 40 J=1,NN
       40    P(I,J)=PSAV(I,J)+DIR(I,J)*GAM
     C*** SET UP EQ. 3.10-19 OF KIRK'S OPTIMAL CONTROL TEXT
             CALL VMULFF(P,B,NN,NN,NP,IA,IA,WK1,IA,IER)
             CALL VMULFF(BTPS,WK1,NP,NN,NP,IA,IA,WK2,IA,IER)
             CALL MADD(WK2,R,FCOF,NP,NP,IA)
             CALL VMULFF(P,A,NN,NN,NN,IA,IA,WK1,IA,IER)
             CALL VMULFF(BTPS,WK1,NP,NN,NN,IA,IA,WK2,IA,IER)
     C*** SOLVE FOR F (THE FEEDBACK GAIN MATRIX)
             IDGT=0
             CALL LEQT2F(FCOF,NN,NP,IA,WK2,IDGT,WKAR,IER)
             DO 12 I=1,NP
             DO 12 J=1,NN
             F(I,J)=-WK2(I,J)
       12    FTPS(J,I)=F(I,J)
             CALL VMULFF(B,F,NN,NP,NN,IA,IA,WK1,IA,IER)
             CALL MADD(A,WK1,V,NN,NN,IA)
             CALL MTPS(V,VTPS,NN,NN,IA)
             CALL VMULFF(P,V,NN,NN,NN,IA,IA,WK1,IA,IER)
             CALL VMULFF(VTPS,WK1,NN,NN,NN,IA,IA,WK2,IA,IER)
             CALL VMULFF(R,F,NP,NP,NN,IA,IA,WK1,IA,IER)
             CALL VMULFF(FTPS,WK1,NN,NP,NN,IA,IA,FCOF,IA,IER)
             CALL MADD(FCOF,Q,WK1,NN,NN,IA)
             CALL MADD(WK2,WK1,FCOF,NN,NN,IA)
             DO 45 I=1,NN
             DO 45 J=1,NN
       45    RID(I,J)=FCOF(I,J)-P(I,J)
       50    CONTINUE
             CALL VNRMFI(RID,NN,IA,XNRM)
             RCF2=XNRM
             RETURN
             END
```

A.1. Listing of a Computer Program (Cont'd).

```
FORTRAN IV G LEVEL  21                DSCTIZ             DATE = 80101            15/57/32

            SUBROUTINE DSCTIZ(A.WK1.WK2.EPS.TAU.IA.NN.ITMX.EXPA.HP)
            IMPLICIT REAL*8(A-H.O-Z)
            DIMENSION A(IA.1).WK1(IA.1).WK2(IA.1).EXPA(IA.1).HP(IA.1)
      C***INITIALIZE THE EXPA AND HP MATRICIES
            TX=0.5*TAU**2
            DO 10 I=1.NN
            DO 10 J=1.NN
            TRM=0.0
            WK1(I.J)=A(I.J)*TX
            IF(I.EQ.J)TRM=1.0
            EXPA(I.J)=TRM+A(I.J)*TAU
         10 HP(I.J)=TRM*TAU+A(I.J)*TX
            ITSUM=2
         20 ITSUM=ITSUM+1
            ATS=ITSUM
            CALL VMULFF(A.WK1.NN.NN.NN.IA.IA.WK2.IA.IER)
      C***FORM THE EXPA AND HP MATRICIES
            DO 30 I=1.NN
            DO 30 J=1.NN
            EXPA(I.J)=EXPA(I.J)+WK2(I.J)
            WK1(I.J)=WK2(I.J)*TAU/ATS
         30 HP(I.J)=HP(I.J)+WK1(I.J)
      C***CALCULATE THE NORMS OF EXPA AND WK2 TO TEST CONVERGENCE
            CALL VNRMFI(EXPA.NN.IA.XS)
            CALL VNRMFI(WK2.NN.IA.XL)
            IF(XL/XS.LT.EPS)GO TO 40
            IF(ITSUM.LT.ITMX)GO TO 20
            ITMX=-ITMX
         40 CONTINUE
            RETURN
            END

            SUBROUTINE MTPS(A.AT.N.M.IA)
            IMPLICIT REAL*8(A-H.O-Z)
            DIMENSION A(IA.1).AT(IA.1)
            DO 10 I=1.N
            DO 10 J=1.M
         10 AT(J.I)=A(I.J)
            RETURN
            END

            SUBROUTINE MADD(A.B.C.N.M.IA)
            IMPLICIT REAL*8(A-H.O-Z)
            DIMENSION A(IA.1).B(IA.1).C(IA.1)
            DO 10 I=1.N
            DO 10 J=1.M
         10 C(I.J)=A(I.J)+B(I.J)
            RETURN
            END

            REAL FUNCTION DREAL*8(C)
            IMPLICIT REAL*8(A-H.O-Z)
            COMPLEX*16 TEMPC.C
            REAL*8 TEMP(2)
            EQUIVALENCE (TEMPC.TEMP(1))
            TEMPC=C
            DREAL=TEMP(1)
            RETURN
            END
```

A.1. Listing of a Computer Program (Cont'd).

```
 TYPE DK2:CNTRL.FOR
       SUBROUTINE CNTRL
       DIMENSION IUDTR(4)
       DIMENSION DSTR(10,4),DTDPX(20,4),UX(10),TOLD(4),TTP(20)
       INTEGER DEFAU
       COMMON/CTRDAT/IMOD,TMP(20,4),TREF,NCAP,VARS(10,4),
     1 NOCTL,NTMP,TAVDM,TMDV,IBDAT,U(20),IHTRDY(10,4),
     2 ICMTH,IUDXX,NCPSS(4),TAVG(4),NCALL(4),NTAU,
     3 CFAC(10,4),F(10,20,4),PREF(10,4),PVAR(10,4)
     4,DTMX(4),DEFAU
      COMMON/COMM/REF(2),IPF,MAUTO,ISW,M6012,WATTR,PL,IERR(10),TRD5
      COMMON/TRSG/NSG(20,4)
       DATA IUDTR,ATCL,IDSTR,TDB/4*1,2.0,0,3.0/
       DATA CFAC/.66,.53,.59,.62,1.93,.58,.55,.53,.59,.37,
     1   .64,.51,.57,.58,1.93,.57,.53,.48,.62,2.61,
     2   .54,.59,.49,.50,2.10,.70,.59,.58,.60,1.82,
     3   .45,.50,.56,.61,1.91,.55,.53,.41,.62,1.91/
       DATA DTMX,TAVG,ICMTH,NTAU,NCPSS,NCALL,GTAV/
     1   4*0.0,4*0.0,1,2,4*0,4*0,5.0/
       DATA NTMP,NHTR,TREF,TAVDM/20,10,288.,1.0/
       DATA DPCOFI,DPCOFC,XLMT/0.3,1.0, 0.05/
       DATA DTDPX/20*5.56,20*6.64,20*6.52,20*6.26/
C***********************************************************
C***THIS SUBROUTINE CALCULATES THE DESIRED HEATER DUTY CYCLE
C***TO THE NEAREST PERCENT.  THE COMPLETION TIME FOR THIS SUBROUTINE
C***IS DETERMINED BY THE OUTPUT PULSE OF THE ONE-SHOT WHICH FIRES
C***THE SOLID STATE RELAYS;  CONSEQUENTLY, THE CALCULATION IS
C***BROKEN INTO SEVERAL MODULES.  MODULES ARE CALLED SEPARATELY
C***FROM THE MAIN ROUTINE FOR A PARTICULAR CAPSULE.
C*****************************************************************
C*****************************************************************
C*******************************************************************
C***DEFINITION OF VARIABLES IN LABELED COMMON
C       IMOD    = INTEGER VARIABLE WHICH DETERMINES THE SUBROUTINE
C                 MODULE TO BE EXECUTED
C       TMP     = MATRIX OF TEMPERATURE DATA OBTAINED FROM THERMOCOUPLES
C       PVAR    = MATRIX OF HEATER POWERS AT 100% DUTY CYCLE, IN UNITS
C                 OF WATTS, AT INITIALIZATION.
C       PREF    = MATRIX OF REFERENCE DUTY CYCLE SETPOINTS
C       TREF    = THE REFERENCE TEMPERATURE TO WHICH THE IRRADIATION
C                 CAPSULES ARE TO BE CONTROLLED
C       NCAP    = THE IRRADIATION CAPSULE FOR WHICH THE CONTROL
C                 CALCULATION IS PERFORMED
C       CFAC    = MATRIX OF CONVERSION FACTORS TO DETERMINE POWER
C                 IN WATTS FROM VARIAC SETTINGS
C       VARS    = VARIAC SETTINGS IN PERCENT
C       NTMP    = NUMBER OF TEMPERATURE DATA FOR A PARTICULAR CAPSULE
C       TAVDM   = ALLOWABLE AVERAGE TEMPERATURE DEVIATION FOR CALCULATING
C                 A NEW HEATER DUTY CYCLE
```

A.2. Listing of the Subroutine for Control of the Electrical Heaters.

```
C        TAV      = AVERAGE TEMPERATURE OF A PARTICULAR CAPSULE
C        IBDAT    = FLAG SUMMED BY UNITY IF A PARTICULAR READING EXCEEDS
C                     THREE SIGMA.  IF IBDAT IS NOT ZERO, A THERMOCOUPLE
C                     HAS PROBABLY FAILED.  ITS READING IS SET TO THE
C                     REFERENCE TEMPERATURE
C        U        = VECTOR OF TEMPORARY DIFFERENTIAL HEATER SETPOINT
C                     CONTROL DEMANDS
C        F        = FEEDBACK MATRIX FOR ALL IRRADIATION ZONES
C        NHTR     =NUMBER OF HEATERS IN A PARTICULAR CAPSULE
C        IHTRDY   = MATRIX OF HEATER DUTY CYCLES TO THE NEAREST PERCENT
C        ICMTH    = CONTROL VARIABLE FOR DETERMING THE METHOD BY  WHICH
C                     THE DUTY CYCLE IS CALCULATED
C                 ICMTH=1:        OPTIMAL/INTEGRAL REGULATOR
C                 ICMTH=2:        CONTROL ONLY AVERAGE TEMPERATURE
C                 ICMTH=3:        DUTY CYCLE REMAINS FIXED AT 80
C                 ICMTH>3:        DUTY CYCLE FIXED AT ICMTH
C        NCPSS    = IF SET TO UNITY, THE CAPSULE IN QUESTION IS DETERMINED
C                     TO BE AT STEADY STATE
C        TAVG     = VECTOR OF  TERMPEATURES FOR EACH CAPSULE
C        NCALL    = VECTOR SET TO ZERO  EACH TIME THE CONTROL
C                     ALGORTHIM PARAMETERS ARE INITIALIZED
C        NTAU     = COUNTER LIMIT FOR DETERMINING STEADY STATE CONDITIONS
C        TAVDM    = ALSO MAXIMUM DEVIATION IN THE AVERAGE TEMPERATURE IN
C                     NTAU CALLS TO ESTABLISH IF STEADY STATE TEMPERATURE EX]
C        NCALL    = COUNTER FOR DETERMINING STEADY STATE TEMPERATURE
C        GTAV     = GAIN FOR TAV CONTROL
C        RXMPR    = MAXIMUM REACTOR POWER
C        RXPR     = REACTOR POWER
C        IDSTR    = SET TO 1 IF CONTROL IS OFFSET BY RX. PR. DEMAND
C        ATCL     = TAV BAND FOR AUTO CONTROL
C        IUDTR    = TAV SWITCH FOR AUTO CONTROL
C        DPCOFI   = DAMPING COEFFICIENT FOR SETPOINT INTEGRATION
C        DPCOFC   = DAMPING COEFFICIENT FOR CONTROL DEMAND
C        IDCTST   = FIXED DUTY CYCLE FOR TESTING
C        TDB      = DEAD BAND FOR SPATIAL CONTROL
C        XLMT     = DEMAND CHANGE LIMIT FOR INTEGRAL CONTROL
C        TMAX     = MAXIMUM TEMPERATURE IN CAPSULE
C*******************************************************************
C
C****COMMENTS*******************************************************
C        1.  CALL CNTRL WITH IMOD=0 TO INITIALIZE.  THE F AND
C            VARS  MATRICIES MUST BE SET BY THE MAIN ROUTINE.
C            NCAP MUST BE SET TO THE NUMBER OF HEATERS CAPSULES.
C        2.  IN THE AUTOMATIC MODE OF CONTROL, CNTRL MUST BE CALLED
C            FIVE TIMES SEQUENTIALLY FOR EACH CAPSULE.  NOTE THAT
C            IMOD IS CHANGED AUTOMATICALLY BY CNTRL AND THAT NCAP
C            MUST BE SET BY THE MAIN ROUTINE. NOTE THAT TREF MUST BE INPUT
C            FROM THE MAIN ROUTINE OR BY THE INITIALIZATION OF THIS
C            SUBROUTINE WHEN CALLED WITH IMOD=0.
C        3.  CONTROL DEMAND IS PRINTED WHEN ICMTH=3
C
```

A.2. Listing of the Subroutine (Cont'd).

```
C*****************************************************************
        IF(IMOD.GT.0)GO TO 800
C***THIS SECTION INITIALIZES PROGRAM CONTROL DATA IF REQUESTED
        IDCTST=80
        IUDXX=0
        RXMPR=30.0
        RXPR=30.0
        DO 10 J=1,4
        TOLD(J)=0.0
        NCPSS(J)=0
        NCALL(J)=0
        DO 10 I=1,NHTR
        DSTR(I,J)=0.0
        DO 7 K=1,NTMP
        DSTR(I,J)=DSTR(I,J)+F(I,K,J)*DTDPX(K,J)
7       CONTINUE
        PREF(I,J)=80
        PVAR(I,J)=CFAC(I,J)*VARS(I,J)**2
        IF(ABS(PVAR(I,J)).LT.10.0)GO TO 8
        PVAR(I,J)=100.0/PVAR(I,J)
        GO TO 10
8       PVAR(I,J)=1.0
10      CONTINUE
        IF(DEFAU.EQ.1)GO TO 15
        WRITE(5,100)
100     FORMAT(/' ENTER 1 TO CHANGE PROGRAM CONTROL DATA. ',$)
        READ(5,*)IPCTR
        IF(IPCTR.NE.1)GO TO 15
        WRITE(5,110)
110     FORMAT(' ENTER REFERENCE TEMPERATURE ',$)
        READ(5,*)TREF
        WRITE(5,120)
120     FORMAT(' ENTER CONTROL METHOD:  1, 2, OR 3 ',$)
        READ(5,*)ICMTH
        WRITE(5,125)
125     FORMAT(' ENTER TAV BAND FOR AUTO CONTROL ',$)
        READ(5,*)ATCL
        WRITE(5,130)
130     FORMAT(' ENTER MAX. TAV DEV. CONTROL PARAMETER ',$)
        READ(5,*)TAVDM
        WRITE(5,140)
140     FORMAT(' ENTER 1 TO OFFSET CONTROL BY RX. PR. DEMAND ',$)
        READ(5,*)IDSTR
        WRITE(5,141)
141     FORMAT(' ENTER TEMPERATURE DEAD BAND  ',$)
        READ(5,*)TDB
        WRITE(5,148)
148     FORMAT(' ENTER CONTROL DEMAND DAMPING COEFFICIENT ',$)
        READ(5,*)DPCOFC
        WRITE(5,149)
149     FORMAT(' ENTER INTEGRAL DAMPING COEFFICIENT ',$)
```

A.2. Listing of the Subroutine (Cont'd).

```
      READ(5,*)DPCOFI
15    CONTINUE
      WRITE(5,150)TREF,ICMTH,ATCL,TAVDM,IDSTR,TDB,DPCOFC,DPCOFI
150   FORMAT(' PROGRAM CONTROL DATA '/
     1 ' REFERENCE TEMPERATURE           =',E12.5/
     2 ' CONTROL METHOD                  =',I4/
     3 ' TAV BAND FOR AUTO CONTROL       =',E12.5/
     4 ' TAV BAND FOR SS CALCULATION     =',E12.5/
     5 ' RX. PR. OFFSET CNT PARM.        =',I4/
     6 ' TEMPERATURE DEAD BAND           =',E12.5/
     8 ' CONTROL DAMPING COF.            =',E12.5/
     9 ' INTEGRAL DAMPING COF.           =',E12.5)
      IF(ICMTH.GT.3)IDCTST=ICMTH
      GO TO 5000
800   CONTINUE
C***DETERMINE THE MODULE TO BE EXECUTED
      GO TO(1000,1001,1000,1980,1990,1995,9000,9001,3000),IMOD
C*******************************************************************
C***THIS MODULE DETERMINES THE TEMPERATURE DEVIATIONS FROM A SPECIFIED
C***REFERENCE TEMPERATURE, THE AVERAGE DEVIATION AND THE MAXIMUM DEV
1000  CONTINUE
      DTAV=0.
      DTXX=0.0
      TMAX=0.0
      DO 1010 I=1,NTMP
      TX=TMP(I,NCAP)
      IF(TMAX.LT.TX)TMAX=TX
      DT=TX-TREF
      TTP(I)=DT
      DTAV=DTAV+DT
      IF(ABS(DT).GT.DTXX)DTXX=ABS(DT)
1010  CONTINUE
      DTMX(NCAP)=DTXX
      DTAV=DTAV/FLOAT(NTMP)
      TAV=TREF+DTAV
      TAVG(NCAP)=TAV
      DAX=ABS(TAV-TREF)
      NCT=0
      DO 1012 K=1,4
      DRX=ABS(TAVG(K)-TREF)
      IF(DRX.LT.5.0)NCT=NCT+1
1012  CONTINUE
      IF(NCT.EQ.4)IUDXX=1
      IF(DAX.LT.ATCL)IUDTR(NCAP)=0
      IF(DAX.GT.ATCL+3.0)IUDTR(NCAP)=1
    GO TO 5000
1001 CONTINUE
C***DISCARD THREE SIGMA DATA AND TRY AGAIN
      VAR=0.0
      DO 1020 I=1,NTMP
      DT=TMP(I,NCAP)-TAV
```

A.2. Listing of the Subroutine (Cont'd).

```
      VAR=VAR+DT**2
1020  CONTINUE
      VAR=VAR/FLOAT(NTMP-1)
      THSG=3.0*SQRT(VAR)
      DO 1030 I=1,NTMP
      DT=TMP(I,NCAP)-TAV
      NSG(I,NCAP)=0
      DT=ABS(DT)
      IF(DT.LT.THSG)GO TO 1030
      TMP(I,NCAP)=TREF
     NSG(I,NCAP)=1
1030  CONTINUE
      GO TO 5000
C*********************************************************************
C***THIS MODULE CALCULATES THE DIFFERENTIAL HEATER SETPOINT CONTROL
C***DEMAND, IN WATTS, FOR A PARTICULAR CAPSULE.  THE HEATER DUTY CYCLE
C***IS CALCULATED IN ANOTHER MODULE.  NOTE THAT THIS CONVERSION TO PERCEN
C***DEPENDS ON THE VARIC SETTING.
1980  CONTINUE
      IH1=1
      IH2=2
      GO TO 2000
1990  CONTINUE
      IH1=3
      IH2=4
      GO TO 2000
1995  CONTINUE
      IH1=5
      IH2=6
     GO TO 2000
9000 CONTINUE
     IH1=7
     IH2=8
     GO TO 2000
9001 CONTINUE
     IH1=9
     IH2=10
2000 CONTINUE
      DO 2020 I=IH1,IH2
      U(I)=0.0
      DO 2010 J=1,NTMP
      U(I)=U(I)+F(I,J,NCAP)*TTP(J)
2010  CONTINUE
2020  CONTINUE
      GO TO 5000
C************************************************************************
C***THIS MODULE CALCULATES THE HEATER DUTY CYCLE FROM THE DIFFERENTIAL
C***HEATER SETPOINT CONTROL DEMAND AND/OR THE BEST ESTIMATE OF THE
C***OPTIMAL HEATER DUTY CYCLE FOR STEADY STATE CONDITIONS.  UPPER AND
C***LOWER BOUNDS ON THE DUTY CYCLES ARE 100 AND 50 PERCENT, RESPECTIVELY.
C***IT ALSO SETS NCPSS(NCAP) TO UNITY IF STEADY STATE CONDITIONS
```

A.2. Listing of the Subroutine (Cont'd).

```
C***EXIST FOR CAPSULE NCAP; OTHERWISE, IT IS SET TO ZERO.
3000    CONTINUE
        IF(IDSTR.EQ.1.AND.PL.GT.25.5)RXPR=0.7*RXPR+0.3*PL
        DO 3010 I=1,NHTR
        UX(I)=0.0
        IF(IDSTR.NE.1)GO TO 3010
        UX(I)=DSTR(I,NCAP)*(RXPR-RXMPR)
3010    CONTINUE
C*******
        IF(ICMTH.NE.1)GO TO 3030
        IF(IUDTR(NCAP).EQ.1)GO TO 4500
        TADJ=1.0
        IF(DTMX(NCAP).LE.TDB)TADJ=0.0
        DO 3020 I=1,NHTR
        RX1=U(I)*PVAR(I,NCAP)
        RX2=UX(I)*PVAR(I,NCAP)
        RXX=RX1+RX2
        IHTRDY(I,NCAP)=PREF(I,NCAP)+RXX*DPCOFC*TADJ
        IF(NCPSS(NCAP).NE.1)GO TO 3020
       XADJ=RX1*DPCOFI
        IF(ABS(XADJ).LT.XLMT)XADJ=0.0
        PREF(I,NCAP)=PREF(I,NCAP)+XADJ
3020    CONTINUE
        GO TO 3090
3030    CONTINUE
C*******
        IF(ICMTH.NE.2)GO TO 3060
        IF(IUDTR(NCAP).EQ.1)GO TO 4500
        DYCH=GTAV*(TREF-TAV)*DPCOFC
        DO 3055 I=1,NHTR
        IHTRDY(I,NCAP)=PREF(I,NCAP)+DYCH
        IF(NCPSS(NCAP).NE.1)GO TO 3055
       XADJ=DYCH*DPCOFI
        IF(ABS(XADJ).LT.XLMT)XLMT=0.0
        PREF(I,NCAP)=PREF(I,NCAP)+XADJ
3055    CONTINUE
        GO TO 3090
3060    CONTINUE
C*******
        DO 3065 I=1,NHTR
        IHTRDY(I,NCAP)=IDCTST
        PVAR(I,NCAP)=U(I)
3065    CONTINUE
3090    CONTINUE
C*******
        DO 3095 I=1,NHTR
        IDC=IHTRDY(I,NCAP)
        RDR=PREF(I,NCAP)
        IF(IDC.GT.100)IDC=100
        IF(IDC.LT.50)IDC=50
        IF(RDR.GT.100.0)RDR=100.0
```

A.2. Listing of the Subroutine (Cont'd).

```
      IF(RDR.LT.50.0)RDR=50.0
      IHTRDY(I,NCAP)=IDC
      PREF(I,NCAP)=RDR
3095  CONTINUE
C*******
      NCPSS(NCAP)=0
      NCALL(NCAP)=NCALL(NCAP)+1
      NL=NCALL(NCAP)
      IF(NL.LT.NTAU)GO TO 4010
      DT=ABS(TOLD(NCAP)-TAVG(NCAP))
      TOLD(NCAP)=TAVG(NCAP)
      NCALL(NCAP)=0
      IF(DT.LE.TAVDM)NCPSS(NCAP)=1
4010  CONTINUE
      GO TO 5000
4500  CONTINUE
      IOFF=0
      IF(TMAX.GT.TREF+10.)IOFF=(TMAX-TREF-10.0)*10.0
      IF(TAV.LT.TREF)NDYC=100-IOFF
      IF(TAV.GE.TREF)NDYC=50
      IF(NDYC.LT.50)NDYC=50
      IF(IUDXX.EQ.1)GO TO 4508
      IF(NCAP.NE.1)GO TO 4508
      IF(PL.LT.28.0)NDYC=0
      IF(TAV.GT.245.0)GO TO 4508
      NDYC=0
4508  CONTINUE
      DO 4510 I=1,NHTR
      IHTRDY(I,NCAP)=NDYC
4510  CONTINUE
5000  CONTINUE
      IMOD=IMOD+1
      IF(IMOD.GT.9)IMOD=1
      RETURN
      END
```

A.2. Listing of the Subroutine (Cont'd).

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